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Review

5G Frequency Standardization, Technologies, Channel Models, and Network Deployment: Advances, Challenges, and Future Directions

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Abstract: The rapid increase in data traffic caused by the proliferation of smart devices has spurred the demand for extremely large-capacity wireless networks. Thus, faster data transmission rates and greater spectral efficiency have become critical requirements in modern-day networks. The ubiquitous 5G is an end-to-end network capable of accommodating billions of linked devices and offering high-performance broadcast services due to its several enabling technologies. However, the existing review works on 5G wireless systems examined only a subset of these enabling technologies by providing a limited coverage of the system model, performance analysis, technology advancements, and critical design issues, thus requiring further research directions. In order to fill this gap and fully grasp the potential of 5G, this study comprehensively examines various aspects of 5G technology. Specifically, a systematic and all-encompassing evaluation of the candidate 5G enabling technologies was conducted. The evolution of 5G, the progression of wireless mobile networks, potential use cases, channel models, applications, frequency standardization, key research issues, and prospects are discussed extensively. Key findings from the elaborate review reveal that these enabling technologies are critical to developing robust, flexible, dependable, and scalable 5G and future wireless communication systems. Overall, this review is useful as a resource for wireless communication researchers and specialists.

Keywords: 5G wireless communication; 5G vision; 5G requirements; 5G enabling technologies; 5G challenges; 5G applications; 5G use cases; 5G frequencies; 5G deployment; 5G channel models

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1. Introduction

The fifth generation (5G) network is presently being deployed worldwide, resulting in a significant explosion of dense mobile applications. As a result, mobile usage is expected to expand by a factor of 1000 by the next decade [1,2]. Consequently, the exponential growth in mobile usage poses serious concerns in the wireless communication ecosystem. In order to handle the expected traffic growth, future wireless communication networks will require a thousandfold increase in capacity. Early mobile communication network generations were built primarily to facilitate human-to-human (H2H) communications, and remarkable success has been reported in meeting the desired data rate and delay requirements [3]. However, more advanced communication technologies are currently being exploited due to the emergence of more inventive technology and services that will cause a profound transformation in almost every area of any global economic development.

Future mobile applications will have a compelling need for better Quality of Service (QoS), Quality of Experience (QoE), higher traffic volumes, and significantly lower costs without sacrificing the required high security. The IMT-2020 family includes 5G technology, which provides exceptional services, including high data rates, quick convergence, high spectral efficiency, flexibility, and uncompromised security. 5G is intended to revamp the current mobile communication technologies, such as IMT-Advanced (4G), by providing more advanced capabilities. 5G introduces three new services to customers: extreme Mobile Broadband (eMBB), enhanced Machine Type Communication (eMTC), and Ultra-Reliable Low-Latency Communication (URLLC). Users can receive fast internet, increased bandwidth, low latency, Ultra-High-Definition (UltraHD) streaming movies, media for Virtual and Augmented Reality (VAR), and several other sophisticated technologies, thanks to 5G eMBB.

The eMTC enables extremely fast, wide-bandwidth machine-type communication over long distances while consuming little power and at a low cost. For 5G to provide low latency and highly dependable communication, the URLLC is a critical 5G feature that will ensure QoS and extremely high reliability, typically not provisioned in earlier mobile technologies [2].

Enabling 5G services and use cases will necessitate additional frequency allocation and flexible spectrum management techniques for mobile broadband. This new frequency standardization should be able to support the newer technologies and services that enable 5G wireless communication. Currently, 5G works on different spectrum bands, such as the licensed, unlicensed, and shared bands of the FR1 and FR2 bands. While the FR2 (24.25 GHz–52.6 GHz) band is perfect for short-range communications with improved data rates, the FR1 (410 MHz–7.125 GHz) bands are suitable for communications via conventional cellular mobile communication lines. Additionally, delivering 5G exceptional services would require integrating older and more modern enabling technologies [4], especially to support services such as multimedia applications, VR/AR, and other highly sophisticated mobile services. Each of these services will necessitate the use of one or more enabling technologies. Key 5G enablers include carrier aggregation, mobile edge computing, dual connectivity, and massive Multiple Input and Multiple Output (mMIMO). The timely deployment of 5G networks depends on the architecture adopted. There are two ways to implement 5G technology. The first is the Standalone 5G deployment paradigm, offering services over an entire 5G network. The second mode, Non-Standalone (NSA), uses a combination of 5G and LTE to deliver services [5].

In the 5G network, application developers and device manufacturers should be able to test and benchmark new mobile applications, devices, and services. A critical aspect of the mobile communications market is to guarantee the correct behavior of dense applications and massive devices to satisfy the requirements of end users. Although these mobile devices have been standardized, there is no adequate consensus on the benchmarking or testing methodologies at the application level. Thus, the need to identify reference deployment scenarios and the definition of new Key Performance Indicators (KPIs) and Quality of Experience (QoE) metrics becomes imperative. Therefore, as in the current survey, it is worthwhile considering the distinct areas for testing and benchmarking, focusing on applications, devices, and mobile network operators.

In the existing literature, extensive research on the various aspects of 5G enablers, such as millimeter wave (mmWave), carrier aggregation, mMIMO, Heterogeneous Networks (HetNets), mobile edge computing (MEC), beamforming, and more, have been conducted [6–16]. However, these works of literature considered and assessed only a subset of these enabling technologies for 5G. To the authors' best knowledge, it is difficult to find a prior work in the literature that comprehensively analyzes the various 5G enablers, advancements, problems, and future directions as in the case of the current contribution.

Our motivation stems from the need for a review allowing 5G and beyond 5G researchers to quickly understand the various 5G technologies and other key topics without wading through a large pool of the existing literature.

One of the closest works reported by Dangi et al. [9] conducted a systematic review of 5G enabling technologies. Although the work is robust and quite elaborate, only nine of the numerous 5G technologies were highlighted. Since no systematic review that provides an all-encompassing discussion and analysis of 5G enabling technologies has been identified, this paper aims to provide a thorough review and analysis of more than twenty (20) of the various enabling technologies for the 5G communication system. The current review also provides useful recommendations on recent developments, difficulties, and future research directions. Specifically, the study systematically evaluated the numerous enabling technologies listed in 5G review works between 2010 and 2022.

Additionally, the current work briefly reviews other key topics within the 5G technology domain, such as 5G use cases and the associated frequency bands, 5G frequency standardization, and 5G propagation channel models. Overall, this work significantly benefits specialists and new researchers working in the 5G and future wireless communication networks domain.

This survey thoroughly examines the various aspects of 5G mobile technology, including potential use cases, channel models, applications, standardization, and a special emphasis on candidate 5G enabling technologies. The following are the key contributions:

- The study presents recent developments in the 5G arena, as well as innovative contributions from the academic community, and provides details on critical features of 5G technology advancement.
- The study conducted a systematic and all-encompassing review of 5G candidate technologies, potential applications, and benefits.
- The study presents the mobile network evolution and discusses the development of mobile communication under various regulatory organizations, such as recent 3GPP releases and 5G development.
- The study presents the existing and emerging 5G use cases, applications, and further recommendations on specific frequency bands for corresponding use cases on the basis of relevant Key Performance Indicators (KPIs).
- The study provides a comprehensive and up-to-date discussion of more than 20 5G enabling technologies, bringing them all together for easy access by other researchers in the wireless communication community.
- The study broadly summarizes the present state of 5G deployment worldwide, including the region, sub-region, country, operator, 5G status, launch date, and initial 5G operating frequency bands.
- The study provides a compact review of non-terrestrial networks (NTN) integration with the 5G system.
- The study discusses 5G propagation channel models and elaborates on the characteristics of each channel and model on the basis of their characteristics, especially with regard to their applicability to 5G wireless networks.
- The study identifies reference deployment scenarios, considering the distinct areas for testing and benchmarking, focusing on applications, devices, and mobile network operators.
- Critical takeaway lessons are presented, and further research directions are highlighted.

The remaining portions of this paper are organized as follows: Section 2 discusses the previous reviews and identifies the key limitations in earlier 5G technology reviews. Section 3 briefly overviews mobile technology evolutions, including the Third Generation Partnership Project (3GPP) releases for mobile communication, IMT 2020 capabilities, and 5G test environments. Section 4 thoroughly examined 5G use cases and spectrum requirements, including 5G applications and recommended frequency bands. Section 5 elaborates on 5G-enabling technologies and the contributing 5G research groups. Section 6 delves into 5G spectrum standardization, 5G global trials, and 5G deployment modes. Section 7 comprehensively discusses 5G radio propagation mechanisms and channel models. Section 8 discusses the challenges of 5G deployment and recommendations for future research work beyond 5G wireless communication systems. Lastly, the conclusion of the review is provided in Section 9.

2. Existing Surveys and Identified Limitations

A review of prior works on 5G-enabling technologies from 2010 to 2022 focused solely on review papers. The main academic databases considered for this review were IEEE Explore, Google Scholar, MDPI, Science Direct, Hindawi, and Springer. These databases contain credible and excellent peer-reviewed research reports in journals, conference proceedings, and review articles. The search phrases 5G and "enabling technologies" were used to query these research databases to obtain relevant papers. A total of 50,679 articles were obtained from the specified databases, all of which were published in English. The articles were reduced to 100 after evaluating their topics, then to 70 on the basis of the relevancy of their abstracts, and finally to 29 after reading through the full texts. The number of articles that satisfy the inclusion criteria retrieved from the various databases is shown in Table 1.

Table 1. The number of articles retrieved from the various databases.

S/N	Article Source	URL	Number of Articles
1	Google Scholar	https://scholar.google.com/ (accessed on 15 September 2022)	23
2	IEEE Explore	https://ieeexplore.ieee.org/ (accessed on 15 September 2022)	1
3	Springer	https://www.springer.com/gp (accessed on 15 September 2022)	3
4	Science Direct	https://www.sciencedirect.com/ (accessed on 15 September 2022)	0
5	MDPI	https://www.mdpi.com/ (accessed on 15 September 2022)	1
6	Hindawi	https://www.hindawi.com/ (accessed on 15 September 2022)	1
Total			29

The frequency of occurrence of 5G enablers in the papers considered is presented in Figure 1. The current survey across the various databases shows that extensive research and analyses have been conducted on the various 5G-enabling technologies. However, these assessments examined only a subset of the various technologies. Most of the critical 5G technologies were not presented in earlier works comprehensively. Thus, in this work, the shortcomings identified in earlier works have been addressed by conducting an extensive survey to identify and combine the various technologies for easy reference.

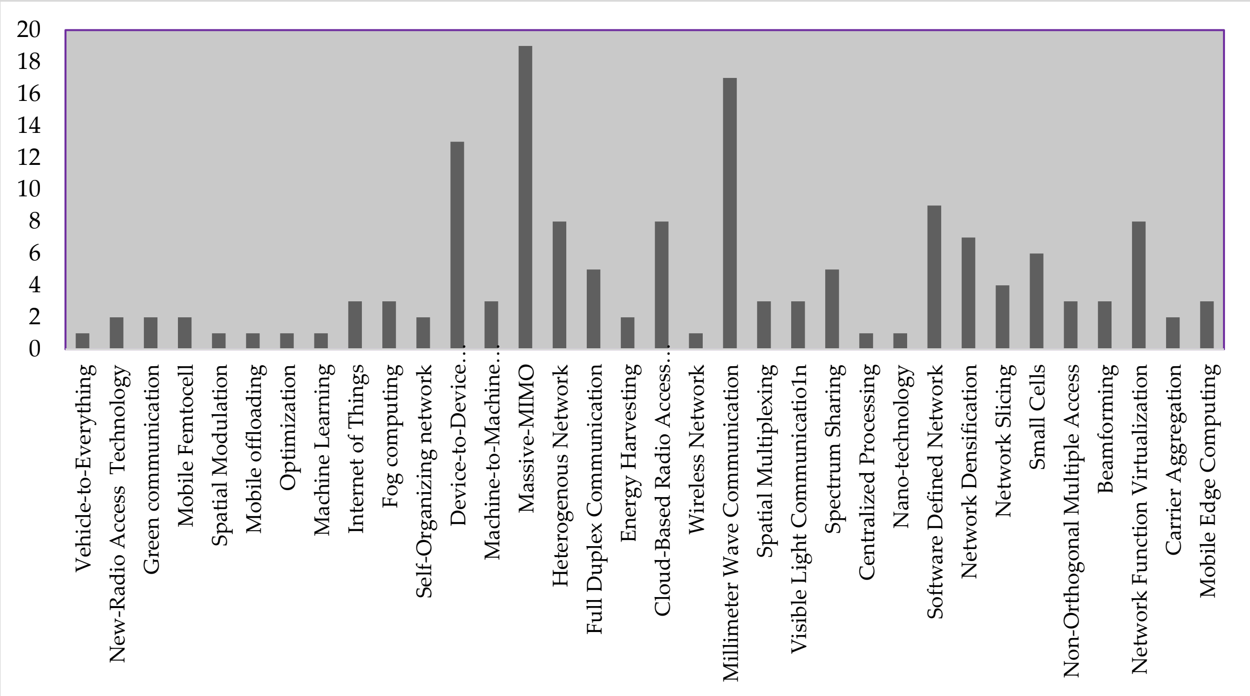

Figure 1. A Summary of 5G Enabling Technologies.

Even though virtually all of these enabling technologies are required for the seamless and satisfactory implementation of 5G, it was discovered that some of them, such as mMIMO and mmWave, are critical to the development of 5G wireless networks, as more than half of the reviewed works presented these technologies. This is not surprising given that they are both critical technologies that enhance, assure, and satisfy the key 5G requirements for huge bandwidth. Next, enablers such as Device-to-Device (D2D), Software Defined Networks (SDN), HetNet, Cloud-Based Radio Access Networks (C-RAN), Network Function Virtualization (NFV), and Network densification, have a large impact on 5G adoption, while others are less prominent. Therefore, more research efforts could be directed toward the technologies that have received less attention from researchers, even though they are equally important to the launch of 5G technology. Table 2 summarizes all the literature reviewed, including the various enabling technologies covered.

Table 2. Limitations of some related works.

References	Vehicle-to-Everything	New-Radio Access Technology	Green Communication	Mobile Femtocell	Spatial Modulation	Mobile Offloading	5G Optimization	Machine Learning	Internet of Things	Fog Computing	Self-Organizing Network	Device-to-Device Communication	Machine-to-Machine Communication	Massive MIMO	Heterogeneous Network	Full–Duplex Communication	Energy Harvesting	Cloud-Based Radio Access Network	Millimeter Wave Communication	Spatial Multiplexing	Visible Light Communication	Spectrum Sharing	Centralized Processing	Nano-Technology	Software Defined Network	Network Densification	Network Slicing	Small Cells	Non-Orthogonal Multiple Access	Beamforming	Network Function Virtualization	Carrier Aggregation	Mobile Edge Computing
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Table 2. *Cont.*

References	Vehicle-to-Everything	New-Radio Access Technology	Green Communication	Mobile Femtocell	Spatial Modulation	Mobile Offloading	5G Optimization	Machine Learning	Internet of Things	Fog Computing	Self-Organizing Network	Device-to-Device Communication	Machine-to-Machine Communication	Massive MIMO	Heterogeneous Network	Full–Duplex Communication	Energy Harvesting	Cloud-Based Radio Access Network	Millimeter Wave Communication	Spatial Multiplexing	Visible Light Communication	Spectrum Sharing	Centralized Processing	Nano-Technology	Software Defined Network	Network Densification	Network Slicing	Small Cells	Non-Orthogonal Multiple Access	Beamforming	Network Function Virtualization	Carrier Aggregation	Mobile Edge Computing
[29]				✓	✓							✓		✓		✓			✓		✓	✓			✓						✓	✓	
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3. Mobile Communications Background

This section covers fundamental topics in 5G, such as the evolution of mobile technology, 3GPP releases for mobile communication systems, 5G development timeline, IMT 2020 capabilities, and the various 5G test environments.

3.1. Evolution of Mobile Technology

Since the first wireless network was established more than four decades ago, the mobile communication system has undergone a noteworthy transformation. The launch of the first-generation mobile network in the early 1980s, coupled with the spontaneous increase in the need for effective communication systems, increased the demand for more connections globally and sped up mobile communications development [40,41]. Wireless communications have, thus, grown to constitute a significant aspect of modern civilization. It has equally changed how society functions, especially after introducing satellite communications, television (TV), and radio transmission. A brief overview of the various stages of technological advancement is given below.

3.1.1. First Generation (1G)

During the 1970s and 1980s, the first generation of mobile networks (1G), which used only analog technology and functioned similarly to a landline phone, was introduced. Despite serving its primary purpose of voice communication, 1G technology had several drawbacks. Coverage and sound quality were poor. It provided no roaming between operators and no system compatibility. Worse, call encryption was not possible with 1G, so security was very poor, and any eavesdropper could easily access the message in transmission [42].

3.1.2. Second Generation (2G)

Unlike the earlier technology, 2G was the first digital system offering mobile voice communication superior to 1G. It was first made available in 1991. In 2G, it was possible to go as fast as 1 Mbps. It has a speed of 64 kbps and transmits voice via digital signals. The 2G has a bandwidth of 30–200 kHz. Short Message Services (SMS), photo messaging, and Multimedia Message (MMS) features are just a few of the services that 2G offers. It makes use of both Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) digital techniques. The most popular 2G mobile standard is the GSM (Global System for Mobile Communications) [41,43].

3.1.3. Third Generation (3G)

The 3G was introduced in 2001 to standardize the network protocol that manufacturers use. The standardization of the "data packets" that drive web connectivity allows users of 3G technology to access data from anywhere in the globe. The popularity of new services such as Voice over Internet Protocol (VoIP) and video streaming has increased as a result of 3G's better data transmission capabilities. A vast coverage area of 384 kbps and a narrow coverage area of 2 Mbps were the data speeds that 3G systems were intended to provide [41,43].

3.1.4. Fourth Generation (4G)

The Long-Term Evolution (LTE) 4G technology was unveiled in 2009. Following its launch, it became widely used, allowing millions of users to transmit high-quality videos. 4G's fast mobile web connection offers up to 1 gigabit per second for static users, making high-quality video conferences, high-definition movies, and gaming services possible. The movement of all communication services to all-IP (Internet Protocol) was made possible to create a common platform for all the existing technologies. A crucial feature of 4G technology is terminal mobility which allows automatic roaming between other wireless networks [42].

3.1.5. Fifth Generation (5G)

In comparison with all previous mobile generation networks, 5G is a significant advancement and a digital transformation foundation. The 5G brings three new services to users: extreme Mobile Broadband, extreme Machine Type Communication, and Ultra-Reliable Low-Latency Communication. eMBB provides users with fast internet, increased bandwidth, lower latency, UltraHD streaming movies, and media for VAR, among several other benefits. In the same vein, the eMTC offers highly fast, wide-bandwidth machine-type communication across long distances, with minimal power use at an affordable price. For 5G to provide low latency and highly reliable communication, the URLLC is the proposed 5G feature that will guarantee excellent QoS and extremely high dependability, which ordinarily are not feasible with the previous mobile technologies [2]. 5G mobile communications technology provides unlimited internet connectivity to users while improving reliability, scalability, and energy efficiency (EE). 5G uses two main frequency ranges: Frequency Range 1 (FR1), also known as sub-6 GHz, and Frequency Range 2 (FR2), also known as millimeter wave, to effectively supply the wide range of services. A 5G connection is best suited to the sub-6 GHz frequency spectrum since it balances capacity and coverage. For the following generation of mobile networks, mmWave will instead deliver ultra-wide bandwidth without compromising the necessary high-speed transmission. However, molecular absorption and distance long-distance transmission are key issues posing limitations to the use of mmWave in 5G.

3.1.6. Sixth Generation (6G)

The Sixth Generation (6G) technology, which was envisioned in 2019–2020 to replace 5G technology, has a main goal of creating an “Intelligent Internet of Everything” and will guarantee better QoS requirements for high energy efficiency, high data rate, high reliability, extremely low latency, very broad frequency bands, and a highly intelligent Deep Learning (DL) and Machine Learning (ML) enabled network [44,45]. 6G can be better described as a self-governing device that will provide a range of communication services and be able to mimic human intelligence and consciousness. Computation-Oriented Communications (COC), Contextually Agile eMBB Communications (CAeC), and Event-Defined uRLLC (EDuRLLC) are the three brand-new sophisticated use case applications suggested for the proposed 6G technology [46–48]. Due to the prospect that the coming technology will employ a much higher spectrum than previous generations, 6G is seen as a technology that will dramatically improve data transmission speed, up to 100–1000 times faster than 5G. Since the technology, which is predicted to be rolled out as early as 2028, is still at its early stage, research is still ongoing regarding how its visions will be fully accomplished [49].

Figure 2 presents a pictorial representation of the mobile communication evolution showing the initial launch years and key characteristics. A comparison of all existing generations of mobile communication in terms of their respective features is presented in Table 3.

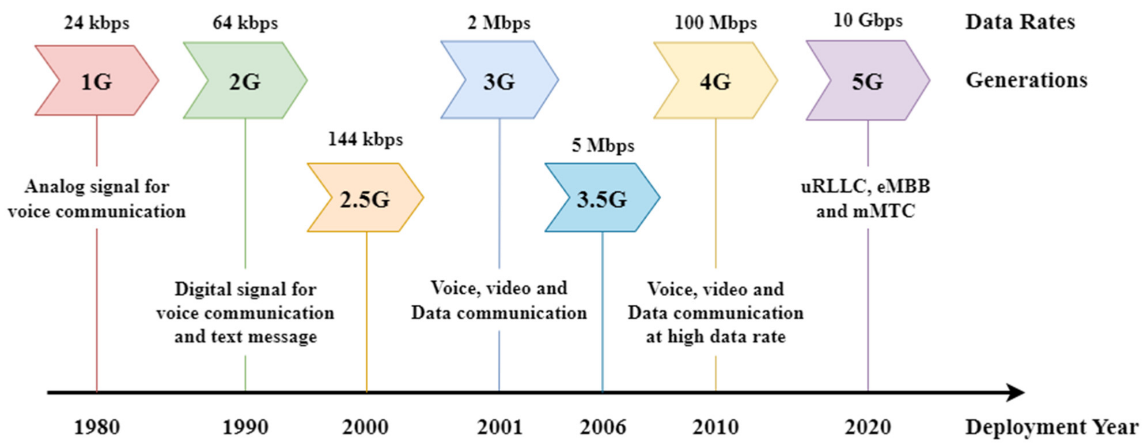

Figure 2. Evolution of cellular communication from 1G to 5G.

Table 3. Comparison of mobile generations from 1G to 5G [9,42].

Generation	1G	2G	2.5G	3G	3.5G	4G	5G
Access Technology	FDMA, AMPS	GSM, TDMA, CDMA	GPRS, EDGE, CDMA 2000	WCDMA, UMTS, CDMA 2000, HSUPA/HSDPA	HSPA, EVDO	LTEA, OFDMA, SCFDMA, WiMAX	BDMA, NOMA FBMC
Switching Techniques	Circuit Switching	Circuit Switching	Circuit Switching	Circuit and Packet Switching	Packet Switching	Packet Switching	Packet Switching
Error-Correction Mechanism	-	-	-	Turbo Codes	Concatenated Codes	Turbo Codes	LDPC
Data Rate	2.4 kbps	10 kbps	144 kbps	384 kbps to 5 Mbps	5 Mbps to 30 Mbps	100 Mbps to 200 Mbps	10 Gbps to 50 Gbps
Frequency Band	800 MHz	800 MHz, 900 MHz, 1800 MHz, 1900 MHz	850 MHz, 900 MHz, 1800 MHz, 1900 MHz	800 MHz, 900 MHz, 1800 MHz, 1900 MHz 2100 MHz	800 MHz, 850 MHz, 900 MHz, 1800 MHz 1900 MHz, 2100 MHz	2.3 GHz, 2.5 GHz, and 3.5 GHz initially	1.8 GHz, 2.6 GHz, and 30–300 GHz
Bandwidth	30 kHz	200 kHz	200 kHz		5 MHz	3.5 MHz, 5 MHz, 7 MHz, 8.75 MHz, and 10 MHz	FR1 (100 MHz) FR2 (400 MHz)
Application	Voice	Voice and Data		5 MHz		Voice, Data, Video calling, HD Television, etc.	Voice, Data, Video calling, Ultra HD video, VR application
Description	Voice conversation	Messaging and Improved data services	-	Voice, Data, and Video calling	-	Voice and Data over fast broadband Internet	Improvement of broadband services to allow IoT and V2X.
Deployment	1980	1990	2000	Surfing the Internet and Introduction of mobile applications	2006	2010	2020
Core Network	PSTN	PSTN and Packet	Packet Network	2001	Internet	Internet	Internet
Security	Poor	Good		Internet			
Handoff	Horizontal	Horizontal	Horizontal/ Vertical		Horizontal/ Vertical	Horizontal/ Vertical	Horizontal/ Vertical
Advantages	Mobility	Security, Mass adoption, Longer battery life	Security, Mass adoption, Longer battery life	Horizontal/Vertical	Better Internet experience	High data rate and Wearable devices	Wider coverage, Improved speed, Fast handover, and Very low latency.
Disadvantages	Poor spectral efficiency and Poor handoff	Low data rate and Low capacity	Slight increase in the data rate	Better Internet experience		Expensive	
				Failure of performance for Internet			

3.2. The 3GPP Releases for Mobile Communication Systems

The Third Generation Partnership Project (3GPP) was founded in December 1998 as a cooperative organization for telecommunication standards. The 3GPP was founded by the

European Telecommunication Standards Institute (ETSI) and other standard development organizations (SDOs) from around the globe to develop new cellular network technology. The seven organizations involved and their countries are as follows:

i. ETSI—European Telecommunications Standards Institute (Europe),
ii. ATIS—Alliance for Telecommunications Industry Solutions (USA),
iii. TTC—Telecommunications Technology Committee (Japan),
iv. ARIB—Association of Radio Industries and Businesses (Japan),
v. TTA—Telecommunications Technology Association (South Korea),
vi. TSDSI—The Telecommunications Standards Development Society of India (India),
vii. CCSA—The China Communications Standards Association (China).

Cellular technology is continually evolving with 3GPP, new features, and services that significantly improve mobile communication systems. The development of a global 3G mobile phone operating on 3G system specifications was the main goal of 3GPP. GSM, GPRS, EDGE, UMTS, HSPA, LTE, LTE-Advanced, and LTE-Advanced Pro 5G standards development and maintenance were later added to the scope [50]. Various 3GPP releases for earlier communication technologies up to the 5G standards, development, and maintenance are presented in Table 4.

Table 4. 3GPP Releases and important features.

3GPP Release	Frozen Date	Main Feature	Data Rate	Spectral Efficiency
Release 99	1999	3G UMTS incorporating WCDMA	2 Mbps	Low
Release 4	2001	UMTS all-IP Core Network		Low
Release 5	2002	HSDPA, IMS	DL: 14 UL: 0.4	Low
Release 6	2004	HSUPA, MBMS, Push-to-Talk over Cellular (PoC),	DL: 14 UL: 5.7	Low
Release 7	2007	Enhancements in QoS and latency, VoIP, HSPA+, NFC integration, EDGE evolution	DL: 28 UL: 11	Low
Release 8	2008	LTE, SAE, OFDMA, MIMO, Dual-Cell HSDPA technologies were introduced	Up to 300 and 75	High
Release 9	2009	LTE/ SAE improvements, Introduction of a Public Warning System (PWS), IMS emergency sessions, WiMAX/LTE technologies	DL: 100, UL: 50	High
Release 10	2011	Introductions of LTE-Advanced, Backward compatibility with Release 8 (LTE), Multi-Cell HSDPA technologies	1 Gbps DL/500 Mbps UL throughput	High
Release 11	2012	Enhancement to LTE-advance, Heterogeneous networks (HetNets) support	1 Gbps DL/500 Mbps UL throughput	High
Release 12	2015	More enhancement to LTE-Advanced, Carrier aggregation (2 uplink carriers, 3 downlink carriers, FDD/TDD carrier aggregation)	1 Gbps DL/500 Mbps UL throughput	High
Release 13	2016	Introduction of LTE-U/LTE-LAA, LTE-M, Elevation beamforming/Full-dimension MIMO, and Indoor positioning	1 Gbps DL/500 Mbps UL throughput	High
Release 14	2017	The start of 5G standardization, Mission Critical Video, and Data over LTE.	10–20 Gbps	High

Table 4. *Cont.*

3GPP Release	Frozen Date	Main Feature	Data Rate	Spectral Efficiency
Release 15	2018	5G support, LTE EPC support for E-UTRAN Ultra-Reliable	10–20 Gbps	High
Release 16	2020	Supports Waveforms above 52 GHz, Massive MTC support, Shared and unlicensed spectrum, Interworking with trusted non-3GPP access, Fixed Mobile Convergence, Network Slicing in RAN, V2X communication with 5G, Broadcast support in 5G	10–20 Gbps	High
Release 17	2022	Reduced Capability (RedCap) Devices, New Radio (NR), Sidelink Enhancements, UAV (Unmanned Aerial Vehicle) Enhancements, Improvements to 5G RAN, Enhancement in 5G IIoT	10–20 Gbps	High
Release 18	2022	Extended reality enhancement, UAV enhancement, Sidelink evolution, Multi-SIM enhancement, Mobile-terminated small data transmission-enhanced mobility support, Network energy saving, Non-terrestrial network, Multicast and Broadcast, Coverage enhancement, MIMO evolution, Improved positioning, AI and ML for NG-RAN	10–20 Gbps	High

3.3. The 5G Development Timeline

The first comprehensive release of the 3GPP's 5G specifications was Release 15 (Rel. 15), which was frozen in two stages: the Non-Standalone variant's specifications were released in December 2018, and the Standalone variant's specifications were released in June 2019 [51]. These standards serve as the foundation for all network deployments and devices that are now being introduced. They have all the essential features required to operate an eMBB service using the newest 5G NR radio technology.

Release 15 of the 5G system contains the foundation for URLLC, particularly in terms of support for low latency [52]. In addition, the machine-type communications technologies, LTE-M, and Narrow Band IoT (NB-IoT), which 3GPP established in Release 13, are added to NR for the mMTC component. These technologies provide unrivaled low-power wide-area performance in a wide range of data rates and deployment scenarios. Release 16, which 3GPP finalized in 2018, added the network slicing and Dynamic Spectrum Sharing (DSS) features made specifically for private 5G networks in addition to continuing prior work on Release 15 features, including mobile broadband. It improved primarily the eMBB service of Release 15.

Release 17 possesses enhanced features from Releases 15 and 16, such as DSS and private 5G network capabilities, and added new features, such as enhanced battery health and satellite access [51]. More enhancements are still expected to come as 5G standard organizations continue to evaluate other prospects of the 5G technology. Details of the 5G standardization timeline are shown in Figure 3.

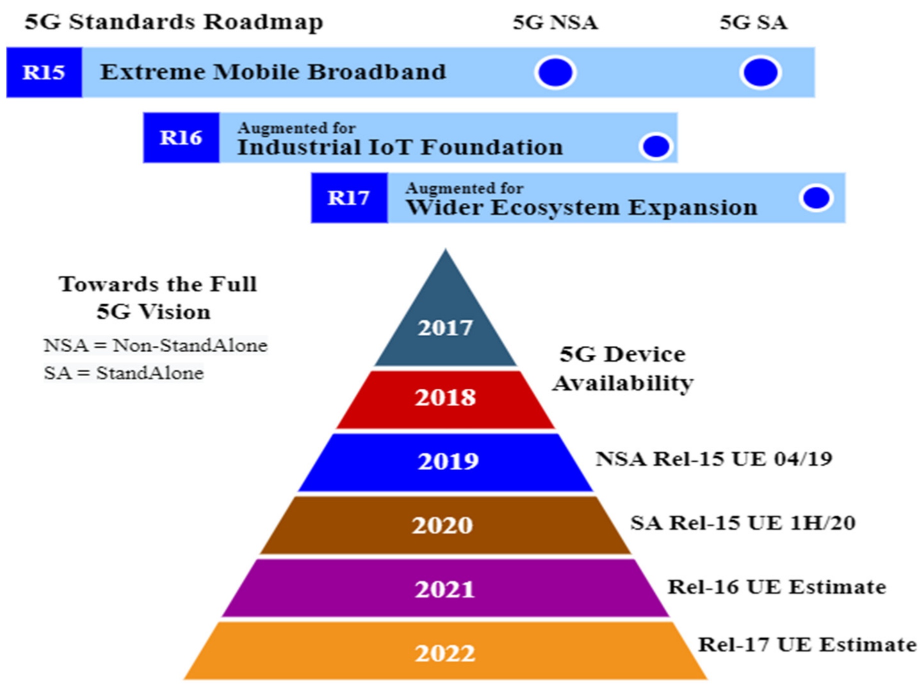

Figure 3. The 5G Standardization Timeline.

3.4. IMT 2020 Capabilities

It is critical to remember that each of the use cases addressed by the IMT-2020 has its own set of technical performance requirements. The fundamental design concepts of the IMT-2020 include flexibility and diversity, making it suitable for established and newly emerging UCs. The IMT-2020 is intended to provide better services than IMT-advanced (4G) in terms of peak data speeds, latency, mobility, connection density, and even network energy usage. For instance, IMT-2020 should provide a maximum attainable data rate of not less than 10 Gbit/s for an eMBB scenario that is more concerned with meeting users' needs for high data rates, and this may even climb to 20 Gbit/s in extreme cases, unlike the LTE that guarantees just 1 Gbps. In contrast to LTE systems, which offer 10 ms of latency, 5G systems will offer a latency of no more than 1 ms to be able to meet applications with extremely low latency needs, such as remote surgeries. In the work of Romano [53], the key capabilities of the 5G NR and LTE systems were carefully considered on the basis of the relevant technical parameters. The work also suggested that these technical parameters may be updated further in later ITU-R recommendations to meet future targets, as they are based on research for IMT-2020 [53,54].

3.5. The 5G Test Environments

The ITU-RM.2412-0 report [54] defines a test environment as a combination of use cases and geographical environments. In the report, a set of five test environments were identified for the IMT-2020 and listed as follows.

i. Indoor Hotspot-eMBB: This is an enclosed location with a high number of pedestrian users, such as offices and shopping malls.
ii. Dense Urban-eMBB: This is a heavily populated urban area with high traffic loads, with a focus on drivers and pedestrians.
iii. Rural-eMBB: This describes a rural location that focuses on providing more extensive and continuous coverage for pedestrians and vehicle users.
iv. Urban Macro-mMTC: This is an urban macro settlement consisting of many machine-type devices which are connected for continuous coverage.
v. Urban Macro-URLLC: The provision of ultra-reliable and low-latency communication is a goal of the macro-urban environment, and a macro-urban location is used to achieve it.

Rural-eMBB, Dense Urban-eMBB, and Indoor Hotspot-eMBB test environments are also suitable for enhanced broadband use cases. In contrast, the Urban Macro-URLLC and Urban Macro-mMTC test environments are suitable for ultra-reliable and low-latency communication and massive machine-type communication.

4. The 5G Use Cases and Spectrum Requirements

This section presents and discusses the various ITU-defined 5G use cases. The use cases and spectrum requirements include the 5G applications, suggested frequency bands based on their specific KPIs, and the 5G applications.

4.1. ITU-Defined Generic 5G Use Cases

In order to ensure seamless and effective deployment of the 5G technology and ascertain the possibility of envisioned 5G services, it is essential to first consider various use cases (UCs) and deployment scenarios. In wireless technology deployments, UCs serve as a way to identify, characterize, produce, and document end users' requirements and expectations from emerging communication technology. The 5G UCs provide us with inputs to specify requirements necessary for defining the building blocks of the 5G architecture [2]. The framework, objectives, capabilities, and various use cases of the "IMT-2020 and beyond" have been defined in an ITU report [54]. In addition, a comprehensive list of approximately 70 5G use cases is contained in the report of the 3GPP SMARTER project [55].

The main objective of the SMARTER project was to develop high-level use cases and identify their corresponding requirements for future 5G deployments. Because these several UCs have some common requirements, those listed in the "SMARTER project" have been streamlined into three generic classes on the basis of performance attributes and service requirements of the individual UCs. Hence, the ITU vision 2020 [56] has defined the three generic UCs which serve as the foundation for 5G technology.

- Enhanced mobile broadband
- Ultra-reliable, low-latency communication
- Massive machine-type communications or massive Internet of things

4.1.1. eMBB

This use case scenario is an enhanced version of the existing LTE broadband, and it allows the integration of new application scenarios and requirements to guarantee an improved user experience. Mobile broadband has been a renowned primary application of the 5G NR technology, and it is currently being embraced by mobile operators to launch the 5G network across countries. The eMBB affords users higher data rates with improved reliability. eMBB will equally address ubiquitous access to wide area coverage and multimedia services, such as 3D video and Ultra-High-Definition (UHD) Screens [2]. The first phase of 5G New Radio Access Technology (RAT) implementation is enhanced mobile broadband [57]. Generally, the mobile broadband UC of 5G will, unlike the 4G, provide improved performance by allowing seamless access to applications requiring high bandwidth for data-driven and human-centric applications, thus increasing the technology lifestyle of end users through offering needed digital services, such as access to cloud-based applications, virtual reality (VR), fixed wireless internet access at homes, and outdoor broadcasting.

4.1.2. URLLC

This set of services refers to delay-intolerant applications that require secure End-to-End (E2E) data transmission and low-latency delivery. The term low-latency implies that data must arrive at its destination at a defined time; otherwise, the data will be of no use, resulting in a loss of reliability [58]. Emerging applications under this scenario should have strict requirement specifications for throughput, latency, and availability, as these capabilities cannot be compromised. URLLC is majorly designed to guarantee a low-latency transmission [59]. The use cases of ultra-reliable communication include applications that perform safety functions and monitoring, such as an autonomous vehicle. Other areas include remote medical procedures, robotics, mobile-enabled industrial manufacturing, power grid management, drone-based delivery, and cloud-based entertainment [60].

4.1.3. mMTC

The mMTC applies to scenarios where many network devices requiring a moderately low volume of delay-tolerant data need to be connected. This scenario is dominated by completely automated applications, such as devices and machines requiring little or no human intervention [61]. One important focus of the mMTC is the possibility of having a completely digital society where every user's communication demands are met with desired high service requirements for high-density connectivity [1]. Smart services, such as smart cities, smart agriculture, business communication, manufacturing, and transportation, are practical examples that fall under the mMTC UCs.

The 5G networks must deliver more flexibility to take care of future use cases and their associated requirements to accommodate other unanticipated UCs that may arise soon. The use cases are built around three KPIs: throughput, device proliferation, and low latency/reliability, as summarized in Table 5. The eMBB use case scenario must guarantee a high peak data rate, user experience data rate, mobility, area traffic capacity, spectrum efficiency, and energy efficiency. The most crucial KPI for the uRLLC scenario is low latency, as it has to provide services for essential applications, such as emergency medical services. High connection density is one of the most crucial capabilities for the mMTC scenario to handle large network users. While some use cases require just a single KPI, others may require multiple KPIs to satisfy the user's requirements. It is, thus, very essential for 5G networks to be able to support a diverse range of applications with their varying KPI requirements in an efficient, reliable, and flexible way.

Table 5. Important KPIs for 5G Generic Use Cases.

Key Performance Indicator	Enhanced Mobile Broadband (eMBB)	Ultra-Reliable and Low-Latency Communication (uRLLC)	Massive Machine-Type Communication (mMTC)
Latency	Medium	High	Low
Mobility	High	High	Low
Connection Density	Medium	Low	High
Spectrum Efficiency	High	Low	Low
User Experienced Data Rate	High	Low	Low
Peak Data Rate	High	Low	Low
Network Energy Efficiency	High	Low	Medium
Area Traffic Capacity	High	Low	Low

4.2. The 5G Applications and the Recommended Frequency Bands

The 5G technology provides several services across various fields of human endeavor. The research communities and other stakeholders have been looking into all of the options for a quick and seamless implementation of the enormous 5G services. Spectrum options, service needs, various access mechanisms, novel waveforms, software-defined networking, and the potential use of massive MIMO are key 5G issues that are still being investigated for efficient technology integration [56]. The spectrum for 5G must be carefully chosen to meet a variety of demands, including those for high data rates, high reliability, the Internet of Things (IoT), and low-latency communication [62].

The three generic use cases supported by the 5G system will require different spectrum specifications to be delivered effectively. To fully serve these various UCs, 5G must use either the lower Frequency Range 1, often called the sub-6GHz band, or the higher Frequency

Range 2, encompassing frequencies above 6GHz. This specification was consistent with a report [63] on 5G spectrum allocation. Spectrum from the low-, mid-, and high-spectrum ranges will be required for 5G to meet the UCs' performance requirements [64]. Combining different spectrum bands will have several benefits and solve many transmission problems. In addition to high data rates, 5G must provide wide area and indoor–outdoor coverage. As a result, the 5GY spectrum solution heavily emphasizes the band below 6 GHz. Over 1200 MHz of spectrum in the 694 MHz to 3800 MHz frequency range has been harmonized in Europe for mobile broadband [65]. However, lower frequencies provide better wireless communication coverage [66].

Table 6 provides an appropriate frequency band for 5G applications based on their specific KPIs. More details on the 5G frequency ranges and the segmentation of the frequency bands into low, medium, and high bands are provided in Table 7.

Table 6. The proposed frequency band for 5G applications is based on their specific KPIs.

ITU Usage Scenario	Main Service	Scenario-Specific KPI	Applications	Deployment Scenario	Proposed Frequency Band	Comment
Enhanced Mobile Broadband (eMBB)	Higher Peak Data Rates User Experienced Data Rates Mobility Increased Traffic Density High-speed Mobility	For maximum data rate: Downlink bandwidth is 20 Gbit/s, and uplink bandwidth is 10 Gbit/s or maximum spectral efficiencies: Uplink: 15 bit/s/Hz, Downlink: 30 bit/s/Hz. User plane latency (single user, small packets): eMBB 4 ms, URLLC 1 ms. 10–20ms control plane latency (from idle to active).	High-speed train	Rural eMBB/Dense Urban-eMBB	FR1	The lower band (below 2GHz) of the FR1 is suitable for providing 5G wide eMBB coverage in rural, suburban, and urban areas. Its mid-band frequency range (between 3 and 6GHz) will provide a reasonable trade-off between high data rates and coverage.
			Broadcasting	Dense Urban-eMBB		
			Blind spots	Rural-eMBB		
			Ultra-low-cost networks	Rural-eMBB		
			Future smart offices	Indoor Hotspot-eMBB	FR2	Higher spectrum bands, such as 28 GHz and 40 GHz, are ideal for applications requiring ultra-high-speed communications and low latencies.
			Virtual reality office	Indoor Hotspot-eMBB	FR2	
			Broadband everywhere (50 + Mbps)	Dense Urban-eMBB	FR1, FR2	The FR1 and FR2 bands will provide the required high throughput, low latency, high dependability, and wide coverage for data-centric applications.
			Media on demand	Dense Urban-eMBB	FR2, FR1	
			Moving hotspots	Dense Urban-eMBB	FR1, FR2	
Ultra-Reliable Low-Latency Communication (URLLC)	Very Low Radio Latency High Reliability Ultra-Reliable Communications	End-to-end latency is 20 ms. 99.999% reliability for remote control information. The bit rate for the remote control (down link): 100 kbps Human control real-time video (1080P).	Tactile Internet/Automation	Urban Macro-URLLC	FR1	Mid-band spectrum of the FR1 is an excellent candidate for the deployment of 5G URLLC services due to its coverage, throughput, latency, and capacity characteristics.
			Emergency communication	Urban Macro-URLLC	FR1	
			eHealth	Urban Macro-URLLC	FR1	
			Smart farming	Urban Macro-URLLC	FR1	
			Smart city	Urban Macro-URLLC	FR1	
Massive Machine-Type Communication (mMTC)	Very High Connection density		Smart agriculture	Urban Macro-mMTC	FR1	The 700 MHz of the FR1 spectrum is a potential 5G band due to its ability to provide wide coverage, which is required for 5G mMTC applications, as well as wide area coverage, which ensures service continuity and requires less infrastructure investment.
			Sensors and actuators network	Urban Macro-mMTC	FR1	

Table 7. Division of 5G frequency ranges.

Classification	General Classification	5G Frequency Band	Sample Application	Comments
Low-band	Below 1 GHz	600 MHz, 700 MHz	Broadcast TV	Spectrum at the lower band (below 1 GHz) is ultimate for deploying 5G coverage and enabling IoT services in urban, suburban, and rural areas.
Mid-band	Above 2 GHz	2300 MHz, 2600 MHz, 3300–3800 MHz, 3800–4200 MHz, 4400–4900 MHz	Fixed satellite, fixed service (point-to-point, point-to-multipoint)	The 3.5 GHz frequency of the mid-band spectrum provides an excellent balance of capacity and coverage.
High-band	Above 6 GHz	26 GHz (24.25–27.5 GHz), 28 GHz (27.5–29.5 GHz), 37–43.5 GHz, 45.5–47 GHz, 47.2–48.2 GHz, 66–71 GHz	Satellite service, space research, earth exploration	High-band spectrum is ideal for ultra-high-speed, short-range applications that require low latency (such as at 26 and 40 GHz).

4.3. Key 5G Applications

Currently, 5G technology supports a wide range of applications that bring user experience to an almost unimaginable mobile communication era. A few of the numerous applications are discussed in this section.

1. Multimedia and Entertainment: Downloading videos account for more than 50% of all mobile internet traffic [9]. Future developments will undoubtedly see a rise in this tendency, spreading video streaming more widely. High-speed 4K video streaming with crystal-clear audio will be available with 5G, creating a high-definition virtual environment on mobile devices. In the future, VR and augmented reality (AR) will be incredibly simple to deploy because of 5G's low-latency and high-definition transmission.
2. Satellite Services: A major challenge with remote areas is limited connectivity due to the unavailability of ground base stations (BS). With the introduction of 5G technology, satellite systems will be deployed to provide network services and ensure unhindered connectivity at remote locations using a constellation of numerous tiny satellites.
3. Smart Homes: Smart home devices and equipment are currently in high demand. The 5G network allows for high-speed communication as well as smart appliance monitoring, bringing the concept of smart homes closer to reality. Smart home products using the 5G network may be readily accessible and set up from distant locations since it provides an extremely fast, low-latency connection.
4. High-Speed Mobile Network: The next generation of mobile network technology, 5G, offers extraordinarily fast download speeds of up to 10–20 Gbps. The 5G network functions similarly to a fiber optic internet connection. In contrast to all prior mobile transmission technologies, 5G effectively delivers high-speed data access as well as voice. Mission-critical and autonomous driving applications benefit greatly from 5G's connection delay of less than one millisecond. 5G will transfer data through millimeter waves, which provide much wider bandwidth and higher data throughput than lower LTE bands.
5. Mission-Critical Applications and Healthcare: Modern medicine is made possible by 5G technology, enabling practitioners and doctors to offer cutting-edge medical services. As a result, all classes can connect via 5G networks. Attending lectures and seminars will be simpler. Patients can now consult doctors virtually for advice via 5G technology platforms. Smart Medical is a tool created by scientists to aid those with chronic illnesses. Smart gadgets, medical internet, smart sensors, medical HD imaging technology, and intelligent analytic systems are all made possible by 5G networks for the healthcare sector. With the help of 5G, one can easily access cloud storage and health information from anywhere globally.

6. Drones for Use in IoT: Awesome photographs from various top views are being delivered from different angles with the use of drones. They are also of paramount importance for inspecting the environment for security reasons. With drone services powered by 5G, one can access high-resolution photos and films for security, surveillance, and other filming purposes.
7. Augmented Reality (AR) and Virtual Reality (VR): with the deployment of 5G, the way games are being played currently will witness a complete transformation, as 5G has been designed with outstanding features for HD gaming. Additionally, virtual reality has emerged as the newest innovation in the tech sector. Virtual reality and its variants will undoubtedly become increasingly visible as 5G connection technology develops. Beyond gaming, 5G will make it possible to experience virtual reality and sports events.
8. Agriculture Industry Use Cases: Despite being the oldest sector in the economy, the agricultural sector of any economy will also benefit tremendously from 5G services. Security of the sector will be improved by installing sensors for surveillance purposes and providing vital crop information, such as the requirement for water, insect control, disease prevention, etc., that will further enhance the timely and healthy germination of the agricultural produce. Additionally, the health of animals, such as cows and sheep, can be easily monitored onsite and remotely with 5G IoT devices.
9. Support for Artificial Intelligence (AI): Large companies with a vast amount of information will have to use AI to process their massive data, and these processes will certainly be accelerated with 5G. Furthermore, when additional sensors are deployed to smart cities, data from these smart sensors must be relayed to allow them to be deployed when necessary. Cellular sensors are in high demand for metering applications, traffic and parking sensors, city lighting, and other uses.
10. Autonomous Vehicles: In the current 5G era, people will have the opportunity to drive autonomous vehicles, a brand-new technology. This can be achieved only with the speed and low latency services that will be guaranteed once the 5G technology is launched. One primary application of autonomous vehicles is the Vehicle-to-Everything (V2X) network, which allows 5G users to connect any of their desired devices to their vehicles.

5. Overview of 5G-Enabling Technologies

A new era in mobile communication has begun as a result of 5G network technology. The 5G mobiles have concurrent access to many wireless technologies, and the 5G station should be capable of combining various traffic flows from diverse technologies [67]. The 5G NR network will be created as an improvement to cellular networks to facilitate extremely fast communications.

To provide exceptional services, the network must integrate older and more modern technologies [38,68]. Furthermore, services such as multimedia applications will necessitate 5G networks to meet several criteria, including increased peak and user data rates, lower latency, better indoor coverage, and many others [10]. As a result, new technologies and services must be advocated for to address issues with data traffic capacity, high data rate, and reliability. Each scenario may necessitate the use of one or more enabling technologies. Among these key enabling technologies are carrier aggregation, dual connectivity, massive MIMO, and mobile edge computing. The majority of these technologies are covered in this section. Figure 4 depicts a diagram of the majority of the 5G-enabling technologies, while Table 8 lists the key 5G requirements and the corresponding enabling technology.

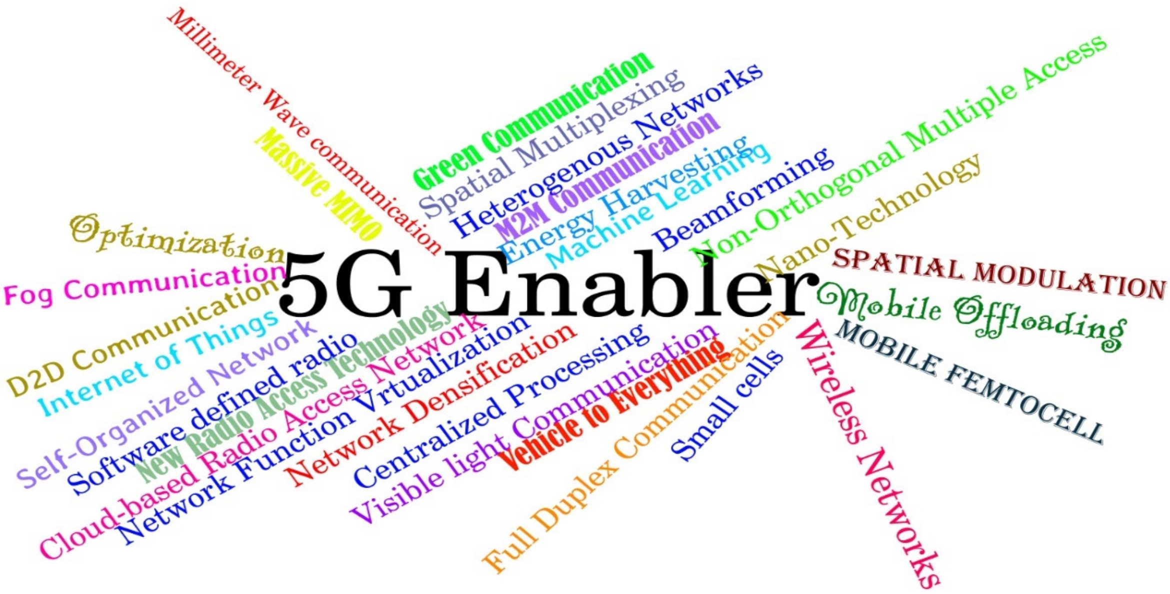

Figure 4. An Overview of Critical 5G Technology Enablers.

Table 8. 5G requirements and the associated enabling technologies.

Requirement	Definition	5G Specifications	Enabling Technology
Peak data rate	In ideal situations, the maximum data rate per user/device (in Gbit/s)	10–20 Gbit/s (peak data rate), 100 Mbps cell edge	Millimeter wave, massive MIMO, dense network, cognitive radio network
User experienced data rate	The maximum data rate that a mobile device can achieve (in Mbit/s) across its coverage area.	1 ms	D2D Communication, MEC
Latency	The amount of time taken for data to travel across a network (in ms).	500 km/h (e.g., for high-speed trains)	Advanced heterogeneous networks
Mobility	Maximum speed (in km/h) at which certain QoS and continuous transfer between radio nodes can be achieved.	106 devices/km^2	Internet-of-things, M2M, D2D
Connection density	The total number of connected and/or accessible devices per unit area (per km^2).	100× greater than IMT-Advanced	M-MIMO, mmWave
Energy efficiency	The number of bits transmitted for every unit of energy consumed	3× greater than IMT-Advanced	M-MIMO
Spectral efficiency	Average data throughput per unit of spectrum resource and per cell (bit/s/Hz).	10 Mbit/s/m^2	mmWave, D2D, NFV
Area traffic capacity	Total traffic volume per geographical area served (in Mbit/s/m^2).	10 Mbit/s/m^2	mmWave, D2D, NFV

5.1. Key 5G-Enabling Technologies

The key enabling technologies are described as follows.

5.1.1. The 5G Millimeter Wave (mmWave)

The microwave bands cannot provide the increased spectrum capacity required by 5G applications because they are currently occupied by early wireless technologies such as 2G, 3G, and 4G, with some bandwidth reserved for other uses. Latest technologies such as 5G are designed to operate on the new millimeter wave spectrum bands, which have a larger spectrum than microwave bands and operate at frequencies ranging from 24 GHz to 100 GHz [22].

Researchers have conducted several works to evaluate the advantages and challenges of deploying a 5G system at the millimeter wave. Qiao et al. [69] investigated whether the mmWave frequency band was suitable for 5G new radio and provided a resource allocation technique for concurrent D2D communication in the mmWave band that maintains network connection and enhances network efficiency. Their findings can be used to simulate D2D communications in the mmWave frequencies in 5G cellular systems. This is due to the fact that huge mmWave BS can be set to achieve a high transmission rate as well as overall efficiency.

In the work of Wei et al. [70], a brief overview of the crowded 1–3 GHz band of the cellular spectrum was presented. The channel parameters relating mmWave signal attenuation due to free space propagation, rain, and atmospheric gases were also discussed, along with other important elements to build up mmWave communications in 5G. The mmWave hybrid beamforming architecture technique was also examined. The authors of the work offered solutions to the blocking effect brought on by penetration damage in mmWave communications.

The requirements and design challenges of mmWave 5G antennas for mobile devices were discussed by Hong et al. [71]. The researchers used 3D planer mesh-grid antenna elements to produce a small, low-profile 60 GHz array of antenna modules. A framework was developed to accommodate the concept of employing antenna components to power cellular telephones on mmWave-based 5G smartphones. They also double-checked the mesh-grid array of antennas with the polarized beam to avoid potential hardware issues. In a related report, Rappaport et al. [72] examined the usage of unused millimeter wave frequency spectrum for 5G wireless connectivity. The authors collected millimeter wave communication measurements for next-generation cellular networks in the congested urban New York City environment.

The availability of high bandwidth is one of the primary advantages of mmWave communications over microwave communications. Even though increased bandwidth may not result in higher rates in the noise-limited zone, the higher propagation losses associated with mmWave frequencies must be carefully considered, particularly at distances greater than 100 m and in NLOS conditions [73]. Furthermore, because its wavelength is significantly shorter than that of sub-6 GHz transmissions, the mmWave signal can fit many more antennas to a compact array. This approach will lead to the large-scale antenna communication range expansion of next-generation mobile networks. However, the beam width is constrained when multiple antenna elements are present.

Despite the numerous advantages of the mmWave band, propagation path loss, which is a common problem with line-of-sight (LoS) communications, is a key challenge. Dry walls and clear glass have relatively low penetration losses for 28 GHz transmissions indoors (when compared with microwave bands). Still, brick and tinted glass have much higher penetration losses (between 28 dB and 40 dB). At higher frequencies, penetration losses frequently increase. Because of the significant penetration loss, it is challenging to conduct indoor measurements using mmWave nodes placed outside and vice versa. In addition, communication in the mmWave band is nearly line-of-sight. Line-of-sight (LOS) obstructions, including people, buildings, and furniture, significantly and negatively impact the connections, making them sporadic. Consequently, the signal is of substantially weaker and significantly reduced quality [11].

5.1.2. The 5G Massive MIMO

The Multiple Input Multiple Output (MIMO) technology is another critical component of the wireless communication system. Massive MIMO is a type of multi-user MIMO technology in which user equipment with only one antenna receives signals on the same time–frequency resource from another single base station outfitted with many antennas [50,74,75]. More than 100 antennas and dozens of antenna ports installed in a base station can be used in a distributed or centralized manner in massive MIMO. Technologies such as channel estimation, reference signal design, multi-user scheduling mechanism, receiving algorithm, and channel information feedback should be optimized and improved for each type of MIMO [76]. The usage of several antennas at the sender and receiver end is made possible by MIMO technology to separate data streams and offer virtual paths onto individual antennas [75,77], even though conventional MIMO performed poorly, its connectivity is less reliable, and its throughput is limited [9]. These issues have been addressed through the use of various MIMO upgrades, such as network MIMO, single-user MIMO (SU-MIMO), and multiuser MIMO (MU-MIMO). Nonetheless, these novel developments are insufficient for end-user applications. Massive MIMO technologies enable 5G networks to differentiate themselves from competitors. By deploying several thousands of broadcast and receive antennas at 5G base stations, 5G massive MIMO will be significantly improved. In addition, when radiated energy efficiency is increased by approximately 100 times, the capacity of 5G networks can increase up to 10 times by employing massive MIMO technology [78]. Figure 5 presents a diagram of the operation of a massive MIMO system.

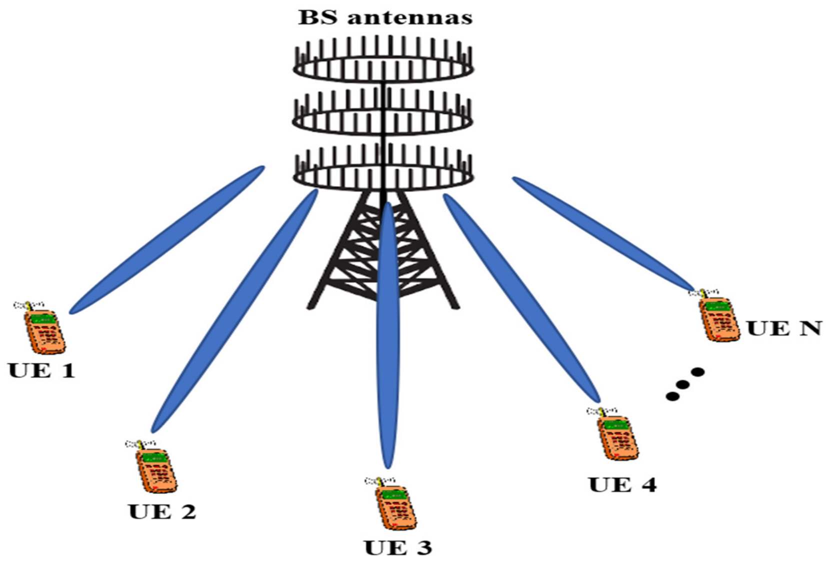

Figure 5. Massive MIMO Scenario.

Various solutions for improving the energy efficiency advantages provided by massive MIMO for 5G have been reported [78–83]. The research made use of massive MIMO technology and offered a comprehensive explanation of the massive MIMO energy consumption model. The Energy Efficiency advantages of huge MIMO systems have been examined using a variety of methodologies. Several methods for improving 5G technology through common EE-maximization techniques for traditional massive MIMO systems were discussed, including reducing the number of antennas, performing simple tasks in real-time at the base station (BS), minimizing power amplifier losses, and reducing the need for Radio Frequency (RF) chains. The authors also described the uplink and downlink services for a 5G massive MIMO system [84,85]. The work maintained a performance matrix that calculates how pilot contamination affects various performance metrics. Furthermore, various applications of massive MIMO were examined, including Orthogonal Frequency Division Multiplexing (OFDM) systems, small cells, higher frequency bands, and massive MIMO IEEE 802. Finally, the work looked at some critical techniques for improving 5G performance through massive MIMO.

An energy-efficient system-sharing strategy based on large-scale MIMO systems was reported in [86], where the costs of circuit energy and transmission energy for resource allocation were considered. Optimization approaches were used for an energy-efficient resource-sharing system to optimize the energy efficiency for individual QoS and energy constraints. The authors also investigated the BS configuration, which incorporates both homogeneous and heterogeneous UEs. During simulations, they stated that boosting energy efficiency heavily depends on the total number of transmit antennas. They emphasized that the maximum energy efficiency was achieved when the BS was configured with 100 antennas serving 20 UEs.

Various strategies for MIMO next-generation wireless communications were suggested in the work of [13,74]. They conducted a comparative analysis in terms of some performance characteristics, such as peak data rate, energy efficiency, latency, throughput, and more, and concluded that MIMO design played a critical role in 5G throughput enhancement.

Uplink and Downlink Transmission of a Massive MIMO Channel

In the subsequent subsections, uplink and downlink transmissions of a massive MIMO channel are considered.

I. Uplink Transmission of a Massive MIMO Channel

The massive MIMO uplink channel is used to transport data and the pilot signal from the mobile terminal to the base station. Consider a massive MIMO uplink system with M base station antennas simultaneously communicating to $N(M \geq N)$ single-antenna users at the same time. If the channel prediction user signal or deterministic pilot signal is $x \in C^N$, the base station signal received during uplink is given by [87,88] as (1):

$$y = Hx + n_{uplink} \tag{1}$$

where $y \in \subset^M$ denotes the base station received signal, H denotes the channel vector between the base station and the user terminal, and elements of $H \in \subset^{MXN}$ are independent and identically distributed with unit variance and zero mean; that is, $H \sim CN(0,1)$. $n_{uplink} \in \subset^M$ is an additional term denoting the addition of interference from the receiver noise and several transmissions defined by (2). The added interference is independent of the user signal x, but it can be affected by the channel H.

$$n_{uplink} = n_{uplink-interference} + n_{noise} \tag{2}$$

II. Downlink Transmission of a Massive MIMO Channel

The downlink channel is used to communicate between the user and the base station as well as to estimate the channel. The base station estimates the channel by employing training pilots. Consider a massive MIMO downlink system in which the base station has M antennas and serves N users with a single antenna. At the same time, the base station delivers independent data to multiple customers [87,88]. The signal received by user k, $y_k \in C^{M\times 1}$, is given by (3)

$$y_k = h_k x_k + n_{download} \tag{3}$$

where h_k denotes a channel vector between the k-th user and the base station, with independent and identically distributed elements with a zero mean and unit variance; that is, $h \sim CN(0,1)$. $x_k \in C^M$ is the signal transmitted by the base station for user k, and $n_{download}$ is the additional noise that is made up of receiver noise $n_{noise} \sim CN\left(0, \sigma^2 I\right)$.

The interference during the downlink is caused by transmitting to other users at the same time and is denoted as (4):

$$n_{downlink} = n_{downlink-interference} + n_{noise} \tag{4}$$

5.1.3. Device-to-Device (D2D) Communication

D2D communication is one of the novels enabling technologies in the 5G network that enables the direct connection of devices, typically during congestion or at cell borders, resulting in an ad hoc mesh network where the intermediary devices might act as a relay for other devices. It is considered the primary technology for establishing point-to-point communications to achieve better coverage area and greater data rates for 5G user devices [4]. D2D communication offers a variety of services which include, but are not limited to, safety, traffic offloading, backhaul network, cellular coverage expansion, battery consumption reduction, reliable communication, and location-based proximity services. Other benefits include power management, spectrum efficiency, better coverage, capacity expansion via radio resource reuse, and decreased overheads due to lowering base stations, device exchanges, and data centers [15,89]. Further benefits of D2D data transmission are that it will be efficient at unloading traffic and improving frequency and space reuse to offer direct communication among local devices without requiring network infrastructure.

D2D communication can improve overall network efficiency by potentially reusing the same frequency resources as traditional infrastructure-based communication [90]. Notwithstanding the several advantages, device-to-device communication also has its challenges; it introduces a variety of interference into the network [91]. Non-negligible intra-cell interference is one of the challenges. Because of the presence of other transmitters, the device's proximity can potentially cause interference. To manage interference, several solutions, such as power regulation, network coding, or interference avoidance multi-antenna transmission, can be used [11]. D2D communication scenarios are shown in Figure 6.

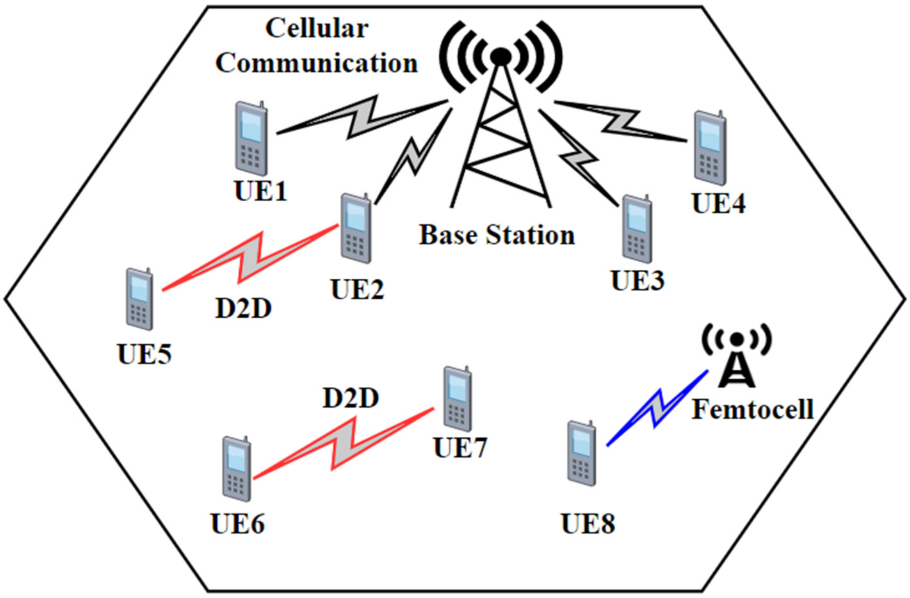

Figure 6. D2D Communication Scenarios.

5.1.4. Machine-to-Machine (M2M) Communication

M2M communication technology is necessary to convey small quantities of time-sensitive data. Intelligent machines may generate, process, and transfer data automatically when they are linked together via M2M connections [3]. The provision of communication services via autonomous sensors, devices, and machines that require little human intervention is called "M2M communication". The capacity of such networks must be sufficient to sustain several concurrent connections over a wide coverage region. With M2M communication, data offloading and aggregation can also be implemented to improve 5G communication and energy efficiency.

5.1.5. V2X Communication

Vehicle-to-everything (V2X) communication is being utilized to develop automotive technology with low latency, higher data rates, and reliability due to the advantages of better traffic information systems, autonomous vehicles, and more dependable safety services. Various examples of communication between vehicles and pedestrians, vehicles and infrastructure, and vehicles and vehicles are shown in Figure 7. Due to its extensive transmission range and low end-to-end latency, D2D communication for cellular networks is better suited for V2X communication [92]. The high mobility in V2X communication will support 5G vehicle network nodes to move at the fastest possible rates, thereby complementing road and traffic safety services.

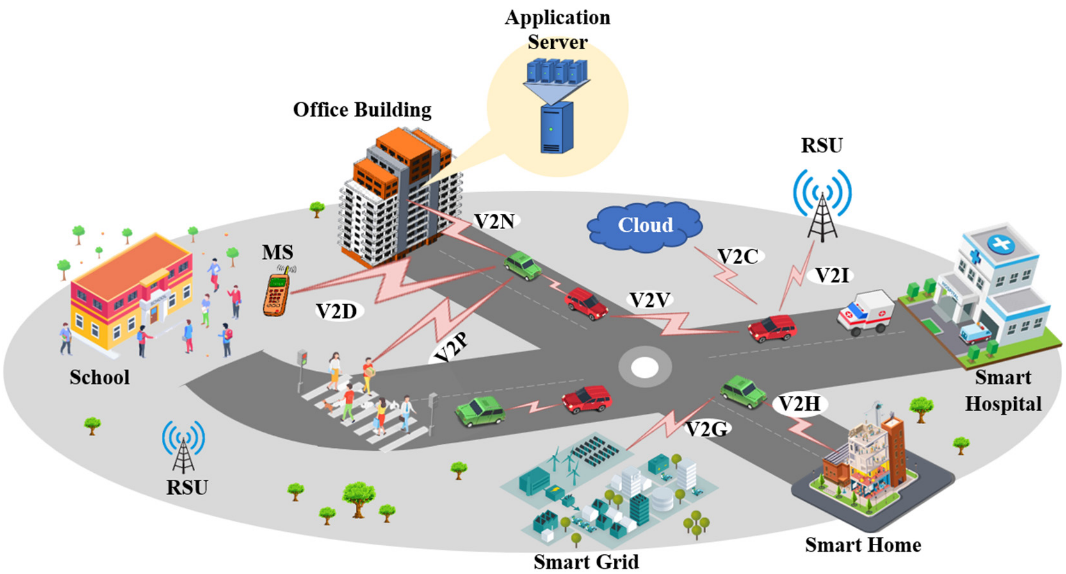

Figure 7. Vehicle-to-Anything Communication.

5.1.6. Network Function Virtualization (NFV)

The purpose of 5G network virtualization is to allow programmable networks for 5G applications by enabling customized network slicing over-dispersed clouds. By abstracting network capabilities and implementing them in software, telecommunication businesses can develop features that meet the criteria of their Service Level Agreements (SLAs) and service models [93]. NFV is accomplished by splitting up a single physical network into several virtual ones, allowing the user equipment to be modified to create as many virtual networks as necessary to meet the needs of each application's QoS. Internally, different blades used for particular tasks are dispersed across the network architecture in a typical NFV [94,95].

With network virtualization, services may be operated flexibly and deployed in many places, hence lowering network load. Numerous virtual tools, including virtual machines, hypervisors, and network operations that require security, are present in the NFV interface. The performance of the system will be impacted if attacks such as cyber- and physical attacks compromise any one tool. The network can be protected from cyber-attacks by intrusion detection systems and firewalls, but trusted computing can shield hypervisors from physical assaults [96].

In order to ensure that only trusted software is running on the NFV interface, trusted computing can be used to ensure data security and the detection of malicious software in virtual functions. Virtual network functions (VNFs) integrated into a service function chaining (SFC) architecture may be quickly deployed and scaled thanks to NFV, which gives network operators the environment they require [97]. Because it provides scalable and adaptable network capabilities, 5G NFV will significantly influence the development of the 5G Internet of Things [98]. To assess the importance of NFV deployment in enabling scalable, resilient, and high-performance communication in 5G networks, the work [7] conducted an overview of the most recent NFV and SFC implementation frameworks as well as major open research challenges. NFV helps network operators by providing the environment required for rapidly deploying and scaling virtual network functions linked in a service function chaining architecture.

5.1.7. Integrated Access Backhaul (IAB)

The inclusion of IAB technology in 3GPP Release 16 was a critical building step in the deployment of mmWave networks. IAB technology is a key Release16 feature in 5G NR that enables quick and affordable mmWave deployments. The IAB terminals share the same interface and frequency for access and backhaul. IAB nodes are required to fill isolated coverage gaps, increase system capacity, and provide fiber coverage for sparse fiber deployments. In addition, the IAB technology deploys networks using a multi-hop strategy and permits the deployment of mmWave base stations with or without fiber backhaul transmission. It operates by employing a fiber or cable connection to have a portion of the deployed BSs act as donor nodes. IAB allows operators to install alternative backhaul where necessary while utilizing their current mmWave spectrum licenses without the need for additional interference studies that would be subject to regulatory scrutiny.

5.1.8. Small Cells or Heterogenous Networks

Small cells are low-power base stations that may be positioned every 100 m to cover small geographic areas, and they are critical to the implementation of 5G wireless networks [83]. Modern data transmission methods utilized by small cells in the 5G networks include MIMO, beamforming, and mmWave. Small cells, or low-power base stations, are used to serve limited geographic areas.

The deployment of small cells is much easier and quicker due to the hardware's simplicity. Compact cells can be placed anywhere because they are light and small [9,99,100]. Femtocells, picocells, and microcells are possible components of the small cell, as shown in Figure 8.

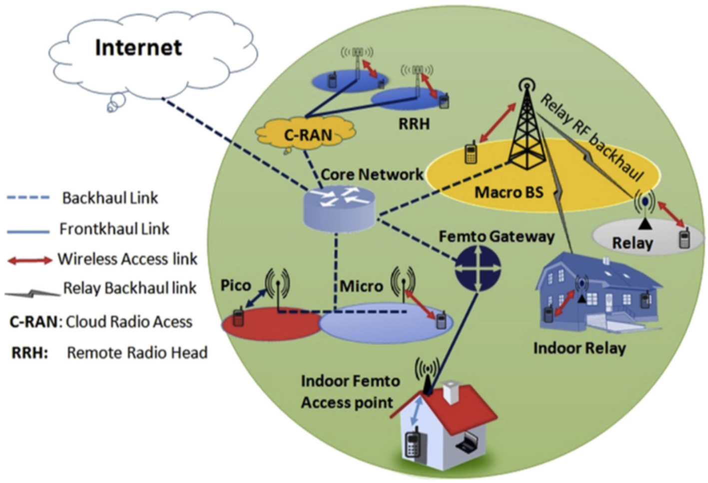

Figure 8. Heterogenous Architecture Consisting of Macrocells, Microcells, Picocells, and Femtocells [101].

Small cells are employed as a relay since millimeter waves cannot travel over longer distances [102]. Small cells help with quick switching and call loss reduction, but they also need security because data relaying compromises data security. To send signals around the obstructions, tens of thousands of compact, low-power base stations are deployed. This enables consumers to continually receive signals without experiencing route loss. Thus, the retransmission process will use less energy at a minimal cost. Additionally, a device near a small cell base station will broadcast data at a low power level, thus reducing the power output of cell phones and extending battery life [20].

The small cell can compress even further and fit in small spaces when millimeter waves are employed, rather than the conventional sub-6 GHz spectrum. Small cells are further categorized into microcells, femtocells, and picocells on the basis of their user capacity and coverage area. Small cells are essential for the delivery of ultra-low latency, high-speed mobile broadband in 5G. Network power consumption, another major challenge confronting the implementation of 5G networks, will also be significantly reduced when small base stations (SBC) are used [101]. In Figure 9, authors [101] presented the result of the power consumption of a transmitter site with a three-sector macro base station (MBS). Their outcome showed that the deployment of small cells significantly decreased power consumption from 4300 to 166 W.

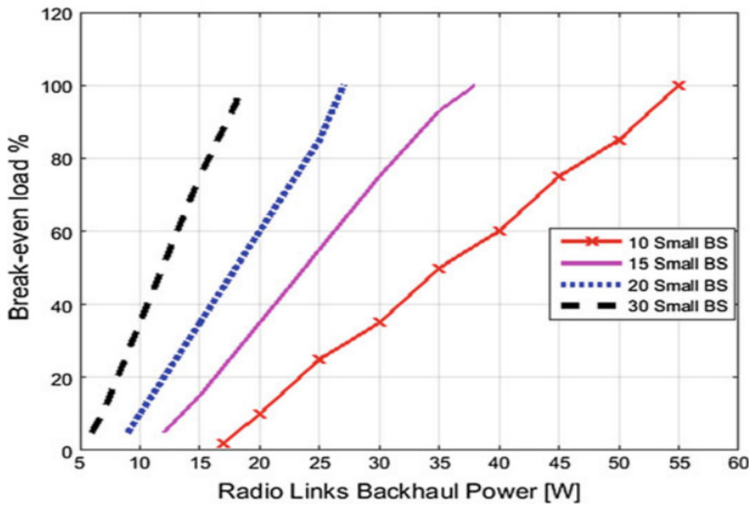

Figure 9. Result of power consumption of MBS and microwave backhaul hub. The figure was reproduced from a paper [101] titled: *Energy Efficiency of Backhauling Options for Future Heterogeneous Networks*; published in Advances on Computational Intelligence in Energy: The Applications of Nature-Inspired Metaheuristic Algorithms in Energy, Green Energy, and Technology; Springer, 2019; pp. 169–194 ISBN 978-3-319-69889-2.

5.1.9. Beamforming

Beamforming is a key wireless network technology that directionally sends signals to the intended destination at minimal loss. 5G beamforming establishes a directed wireless network transmission to the receiver. It is difficult to move signals in a specific direction in conventional systems. This problem is addressed by using small cells that can send signals in a specific direction to a device such as a laptop, mobile phone, autonomous vehicle, or IoT device. Beamforming can be classified into digital, analog, and hybrid beamforming [9].

In massive MIMO systems, the base station can provide data to the user over several pathways, and beamforming controls packet movement and predicted arrival time to allow more users to submit data simultaneously. Because millimeter waves cannot pass through obstructions and do not propagate over longer distances due to their shorter wavelength, beamforming is employed to provide concentrated beams to consumers. As a result of beamforming, a user can receive a powerful signal while avoiding interference from other users [87]. When beamforming is employed in 5G communication networks, energy efficiency and conservation can be maximized.

5.1.10. The 5G Non-Orthogonal Multiple Access (NOMA) Principle

Another essential 5G wireless system component is the NOMA principle, which allows several users to exchange data in a small cell. It is highly advantageous for heterogeneous networks. On the most basic level, it works by allocating the same resources in terms of time, area, and frequency to different users. NOMA is separated into code–domain NOMA and power–domain NOMA [103]. While code–domain NOMA can enhance 5G connectivity by enhancing the spectral efficiency of massive MIMO, power–domain NOMA is more commonly used in 5G wireless networks due to its ability to integrate with a wide range of wireless communication techniques, including MIMO, beamforming, space–time coding, network coding, full–duplex and cooperative communication, among others [9].

NOMA can benefit a variety of uses, including massive machine communication, machine-to-machine, and Ultra-Dense Networks (UDN). This ground-breaking technology also has high spectrum efficiency, high-speed massive connectivity, high reliability, and low latency. Furthermore, when resources for bandwidth are assigned to users with minimal Channel State Information (CSI), the traditional Orthogonal Frequency-Division Multiple Access used by 3GPP in 4G LTE networks results in unusually low spectral efficiency. This issue was resolved by employing NOMA [9,104], which provided users access to all subcarrier channels. This increased spectral efficiency by allowing users with high CSI to use bandwidth resources formerly reserved for users with low CSI. Despite the many advantages of NOMA, there are some disadvantages as well. For instance, NOMA requires a lot of Computer Processing Unit (CPU) resources from many consumers at high data rates to execute the SIC algorithms. Secondly, managing power allocation optimization when users leave networks is a challenging problem in NOMA [105].

A look at a basic NOMA model with two users, which clarifies the fundamental principles of the model, was provided by [106]. Their research was then broadened to encompass an overall architecture, including multicarrier support on each sub-carrier, an arbitrary number of consumers. Resource sharing and multiple-input–multiple-output NOMA are investigated in performance evaluation using current methodologies. The authors included the essential components of NOMA as well as potential research requirements. They examined the two-user SC-NOMA and the multi-user MC-NOMA designs to demonstrate the fundamental strategies and conventions of NOMA. The key features and challenges of NOMA technology were also discussed. The authors [107,108] investigated non-orthogonal multiple access (NOMA) from its inception to recent advances. They contrasted NOMA approaches with traditional OMA techniques in the context of information theory. The NOMA schemes were formally discussed as belonging to the power and code domain, including design concepts, operational principles, and features. Performance, spectrum efficiency, and receiver complexity are utilized as comparative criteria. The expected outcomes of NOMA and how it would meet the essential needs of 5G mobile communication systems, such as enormous connection and reduced latency, were highlighted.

5.1.11. Radio Access Technology (RAT)

The design of the radio access technique had to be reconsidered in light of the various needs for 5G networks. Due to the growing demand for gigabit speeds, the underlying radio access technology ought to be capable of transmitting data at higher rates. Given the finite and expensive nature of the spectrum, spectral efficiency is a crucial component of radio access technology that will enable gigabit speeds.

Certain 5G services and applications, such as tactile Internet, holography, and mixed worlds, require millisecond latency. This constrains the radio access mechanism's latency perspective, allowing for the lower latency required at higher layers to be realized. Devices may not necessarily be connected to the BS in other applications such as IoT. These devices' power restrictions prevent them from being fully synchronized with the BS. As a result, the multiple access technique used should be able to handle slack or, better yet, no synchronization. Interference is a risk in multi-access strategies, as it is in other wireless systems.

Finally, the radio access technique should be power efficient to avoid exhausting the power of low-power devices. The fifth generation cellular network is expected to provide exceptional data speeds when compared with high-speed wired lines. Because the future network system will be heterogeneous, small cells will be absorbed into macro-cells. As a result, the cells will be fragmented into disparate radio access networks that will be linked to nearby RATs, such as Wi-Fi and other licensed networks [35,109].

5.1.12. Green Communication

Green communication is used to minimize base station energy consumption since the base stations require a significant volume of electricity for reliable operation. The ecosystem suffers greatly when a large number of base stations are used. Reduced RF transmits power and has the potential to increase energy efficiency. Significant energy is saved when reference signals are delivered only among a base station and user equipment rather than in each sub-frame. Another approach for reducing energy consumption is to utilize a duty cycle device, which switches off some base stations when there is little traffic. Service providers can also employ renewable energy sources, such as solar and wind energy [15].

The number of networked devices is predicted to grow tenfold during the next decade, as is the volume of data [3]. While meeting these goals is difficult, we must also do so cost-effectively and for the long-term. Although mobile communications now account for less than 1% of CO_2 emissions, we should strive to reduce them even further [35]. In addition, power bills, which have already become a critical challenge due to high operating expenses, will also be reasonably reduced. Thus, reducing energy usage and shifting to green communication options are crucial for the environment and the economy.

5.1.13. Mobile Femtocells (MFemtocells)

In the mobile femtocell idea, the moving network (or mobile relays) is a viable solution for boosting the spectral efficiency of next-generation networks. MFemtocells are small cells that can be easily put in moving buses, trains, and vehicles, allowing the BS to execute data sending and receiving with onboard consumers [29]. The deployed femtocells frequently move, forcing them into areas with poor eNB signal strength. Thus, they demand continuous handovers with neighboring base stations, which must be exceedingly rapid to offer smooth wireless access to the end user as they move. Furthermore, due to the frequency of connection change requests and the necessity to accomplish the requests within a limited amount of time, MFemtocells complicate the entire handover process, causing signaling load and frequent connection drops in the network. The MFemtocell concept tremendously benefits wireless cellular networks since it dramatically boosts spectrum efficiency and average throughput. With a few added capabilities, MFemtocell manages traffic as if it were a single UE (or transceiver).

5.1.14. Spatial Modulation (SM)

Multiple antennas at the transmitter and receiver end effectively boost spectral efficiency while reducing hardware complexity. Addressing inter-cell interference, in contrast, makes implementation more difficult because signal processing at the BS demands a large amount of energy. Spatial Modulation (SM), one of the most effective methods for reducing the complexity of an MIMO network, views the antenna arrays as a spatial constellation diagram, with each antenna in the system carrying a sequence of information bits [29]. After a successful match of the incoming symbol with the existing symbol on the antenna, whose spatial position is encoded with the data needed to be broadcast, this method allows broadcasting from a single antenna of the antenna array at once.

Spatial modulation boosts communication network performance greatly and takes advantage of huge MIMO benefits for enhanced energy economy in wireless communication systems [110]. SM, on the other hand, sacrifices a spatial degree of freedom due to the logarithmic increase in multiplexing gain with an increasing number of antennas at constant energy dissipation (which induces a capacity gain with no supplemental bandwidth requirements as a result of the transmission of different data streams using the same resources in a spatial domain). SM is regarded as an important underlying technology for 5G networks in satisfying the expectations of emerging data-hungry technologies because of its several advantages [110].

5.1.15. Local Offloading

5G networks are intended to swap resources to fulfill the varying traffic demands of heterogeneous users/applications (e.g., 4 K high-definition video streaming and IoT). Certain services may benefit from local processing at the network's edge, but others, owing to privacy or legal considerations, may require centralized processing. Thus, local offloading solutions are necessary for a heterogeneous environment to enable extremely high bit rates, low latency, and low power consumption by using UE proximity; this decreases network load, boosts spectrum efficiency, and leverages direct transmission among devices. In this heterogeneous context, the localized breakout of chosen traffic closer to the edge (i.e., offloading the network core) is required, as is the usage of different gateways for traffic with variable connection and mobility needs [27].

5.1.16. 5G Machine Learning

Another essential characteristic of 5G systems is the ability to deploy AI/ML (Artificial Intelligence and Machine Learning) at pre-defined network locations. Given that the SBA's UE and 5G core network functions already supply computing resources to execute ML algorithms, the significant news is that it smartly exploits the utilization of Multi-access Edge Computing (MEC) inside 5G standards to push Machine Learning to the edge of the telecom network.

In 5G mobile communication systems, several machine learning (ML) methods were applied to solve various difficult issues, but it involves significant hand-tuning. There are three types of machine learning approaches: supervised, unsupervised, and reinforcement learning. Each of these strategies substantially influences the performance of 5G wireless networks [9].

5.1.17. The 5G Internet of Things (5GIoT)

Another technology affecting many parts of the 5G cellular network environment is the Internet of Things (IoT). The development of the 5G mobile network is important to the evolution of the Internet of Things, which will link many things to the Internet, including sensors, gadgets, items, and appliances. These apps will gather vast information from numerous devices and sensors. 5G will enable extremely rapid Internet connectivity for data gathering, transport, control, and processing. Because of its flexibility, unused spectrum availability, and inexpensive implementation costs, 5G is the most efficient technology for IoT, which aims to create a network of linked. These heterogeneous devices capture data in real time over a limited amount of time [111]. 5G will provide extremely fast Internet access for data gathering, transport, control, and processing. Because it is a flexible network with an unused spectrum and allows a very low-cost deployment, 5G is the most effective technology for IoT [112]. The 5G IoT applications include smart homes, smart cities, smart farming, autonomous cars, and industrial IoT.

In the long run, all devices that benefit from communication networks are expected to be linked, and the number of connected devices will surpass human devices. Connectivity has become a real concern for M2M communication due to the rising availability of mobile broadband. The tremendous traffic growth expected from machine-type communication as a result of billions of linked gadgets, on the other hand, would lead the network to become overcrowded. As a result, network connection and capacity must be boosted by orders of magnitude, which may be accomplished by the implementation of additional 5G technologies, such as network densification, dense small cell deployment, and massive MIMO [26].

The Internet of Things may also be thought of as a network of ordinary physical items, such as cars, appliances, electronics, and buildings. Wearable smartwatches, health monitors, washing machines, and microwave ovens are examples of IoT goods that detect data and transfer it to a distant server, often through the Internet. The server can also give commands to the device remotely. The server data is then analyzed to understand more about the underlying activity [35].

IoT and 5G might easily be combined with more powerful wireless technologies to form the same ecosystem capable of meeting the present demand for IoT devices. 5G will have an impact on both nature and the expansion of IoT devices. As the 5G process proceeds, multinational companies will discover the need for cross-industry collaboration in defining and expanding the 5G system [113].

5.1.18. Fog Computing

Multi-access Edge Computing (MEC) is related to the Fog Computing (FC) paradigm, which was presented by Cisco in 2012 and stretches cloud computing capabilities to the edge of the network to build a highly virtualized platform that delivers computing, storage, and networking services between end devices and traditional data centers [34]. Low-latency communication is a key property of FC, which makes it more suitable for 5G communications. Data must be centralized in some applications, which may necessitate the use of cloud computing. This "cloud model" can be extended to edge fog networking, which is a system-level horizontal architecture that distributes resources and services everywhere along the Cloud-to-Things continuum. Fog and Cloud fusion can provide device and service consolidation, as well as optimization of tenant and virtualized service life-cycle management, data policy management enhancements, and application and data management integration [25]. IoT services can also benefit from location awareness and geographical distribution features of fog computing [35].

5.1.19. Self-Organizing Network (SON)

The 5G networks are intended to establish a heterogeneous and dense network with a variety of access modalities to give a seamless user experience. The expected density makes designing the network layout of 5G networks difficult. As a result of the dynamic nature of the process, SON strives to automate network configuration, resulting in easier deployment and operation as well as increased performance. This technology is regarded as a critical enabler of these goals and a critical facilitator of new UCs, such as autonomous driving and tactile Internet, which necessitate a fundamental shift in network management with significantly greater automation and dynamic predictive resource allocation [25].

5.1.20. Multi-Access Edge Computing (MEC)

The potential to deploy cloud computing capabilities within Radio Access Network closer to 5G end users can increase the performance of 5G applications and minimize network congestion. Mobile users can utilize MEC to access cloud computing and IT services at the nearest position, such as the edge of the base station [76]. This enables it to precisely meet the criteria of the 5G standard for low latency and high bandwidth.

MEC further enables 5G networks to properly evaluate data collected from several sources and offer locally relevant information for URLLC use cases, such as smart driving services [114]. This capability will allow 5G applications to embrace improved services that need very low latency and large bandwidth effortlessly. These programs will have rapid, real-time access to radio network data. High bandwidth and extremely low latency computers are required for current automobile applications and services. Because MEC extends cloud infrastructure to where people and things connect to the network, additional processing and storage equipment is required, which significantly influences base station design and manufacturing. Core networks can be made less crowded from their perspective by providing numerous services and storing data at the network edge [64].

MEC acts as a barrier between the end user and the cloud server, allowing the user to move closer to the cloud. This edge now offers all services, including virtual software, video conferencing, and other services, thereby boosting the efficiency of cloud computing. In addition, because MEC can be viewed remotely, it reduces the requirement for the user to download the complete program on his device, thereby improving device performance. Beck et al. [115] offered a taxonomy for mobile edge computing applications and evaluate technological potential and restrictions. There is a list and explanation of the many application categories that benefit from edge deployment. These applications were carefully classified on the basis of technical characteristics. The work established that effective MEC deployment in 5G networks raises the overall performance of the 5G architecture.

The 5G network and the concept of edge computing in MEC allow real-time, on-demand delivery of IoT applications and services, such as telemedicine, autonomous vehicles, industrial automation, and data processing from IoT sensors [116]. Because of the dense cell location, inter-cell interference is conceivable. For example, interference from surrounding cells and the macro-cell may affect the micro-cell. A 3GPP project answer to these challenges is an inter-cell collaboration [115,117].

5.1.21. Access Point Densification

Densification of access points refers to the establishment of additional base stations and access points per unit of area. The success of the 5G rollout will surely be contingent on access point densification, which means boosting available network capacity through the deployment of more cell sites, such as radio access networks, in-building wireless, macro sites, and small cell deployments. Network densification will be most effective around metropolitan areas and major venues with a high density of digital users [118].

Network densification is critical for 5G because digital device consumers continually demand better speeds and more connectivity. Driverless automobiles and remote surgeries are two examples of future digital services that rely on the enhanced connection and quicker speeds of 5G networks. Small cells are needed to improve 5G coverage and capacity, and certain vehicles can assist the public network by acting as self-deployed moving cells.

Sector-splitting and large multiple input multiple output technologies can potentially increase the number of antennas and tiny cell sites. Network densification is crucial for 5G because digital device users always want faster speeds and more connection. It must be capable of transmitting data at ten times the pace of 4G while maintaining a consistent connection [118–120].

5.1.22. Carrier Aggregation

The 3GPP introduced carrier aggregation technology to increase the uplink and downlink channels' throughput, capacity, data rates, and overall network performance [121]. The third-generation partnership initiative designated carrier aggregation as one of the important technologies for the fourth generation of mobile systems (3GPP Release 10 standards) [52].

Carrier aggregation allows for the concatenation of up to five LTE carrier components (CCs), increasing the capacity and data rate (uplink and downlink) of the system. The bandwidth possibilities for LTE-Release 10 are 1.4, 3, 5, 10, and 20 MHz. Carrier aggregation can support up to five CCs, guaranteeing a 100 MHz maximum bandwidth (5 x 20 MHz) [122]. The 3GPP originally made carrier aggregation available in Release 10, although it was only possible in the downlink. In Version 11, the approach was improved by enabling up to two CCs in the uplink. Later, in Version 12, time division and frequency division duplex carrier aggregation were included [122].

In Release 13 (LTE Advanced-PRO), the attainable bandwidth was raised to 640 MHz by raising the number of 20 MHz CCs that could be aggregated from 5 to 32 [123]. A new technology known as Dual connectivity (DC) enables the aggregation of LTE and 5G NR carriers, allowing for up to 1 GHz of aggregated bandwidth. Dual connectivity is supported by the 5G NR, which allows it to support up to 16 CCs. Due to 5G DC, carrier aggregation is now achievable in the 5G FR1 and FR2 frequency channels [121].

Contiguous and non-contiguous carrier aggregation (CA) are the two main types. While non-contiguous CA separates surrounding component carriers, contiguous CA utilizes a larger spectrum and integrates many neighboring component carriers. Non-contiguous CA is further subdivided into intra-band non-contiguous, in which a UE is assigned to numerous CCs dispersed throughout the same spectrum band, and inter-band non-contiguous, in which the clustering of numerous CCs from various bands with distinctive characteristics, such as one from the bands of 2100 MHz and 800 MHz, is permitted to create a broad spectrum [124]. Figure 10 shows the LTE carrier aggregation and 5G-LTE dual connectivity. In Figure 11, the types of CA aggregation are presented.

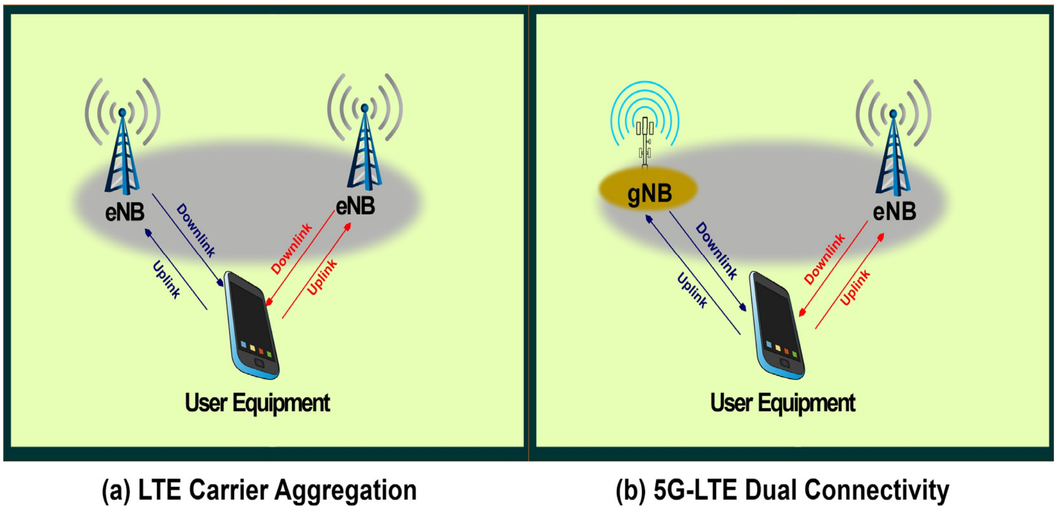

Figure 10. LTE CA and 5G-LTE Dual Connectivity.

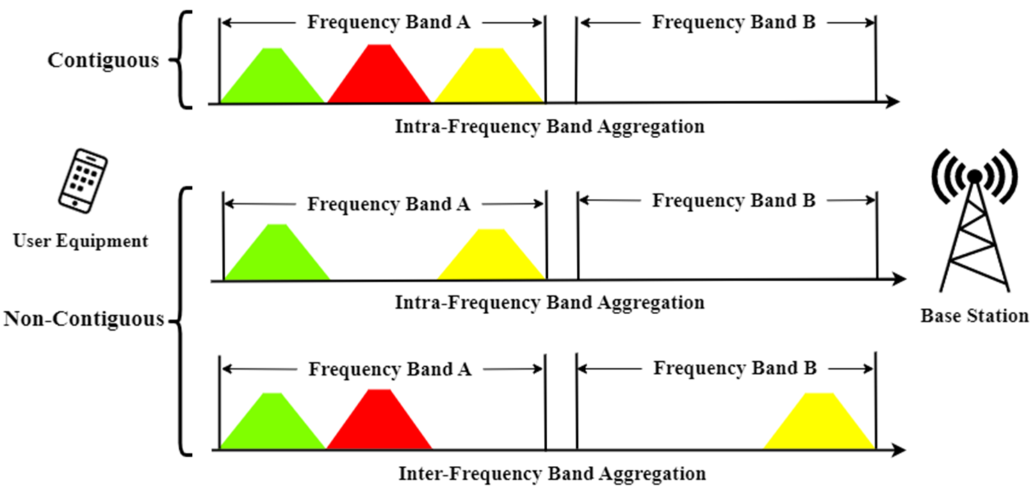

Figure 11. Contiguous and Non-Contiguous Carrier Aggregation.

Alkhansa et al. [122] developed a system-level LTE-A carrier aggregation solution that makes use of the Wireless Fidelity (Wi-Fi) spectrum. They suggested a system architecture for an aggregation mechanism based on the concept of mixing LTE carrier components with Wi-Fi carrier components. They presumed the LTE system would run in a CA mode, borrowing Wi-Fi spectrum, and their study demonstrated that this CA mode was consistent with the LTE-Advanced physical layer standards, making it theoretically conceivable and adaptable to future beyond 5G wireless systems.

Carrier Aggregation (CA) is a significant 5G technology that aids in spectrum use. Joda et al. [125] developed a methodology to improve CC selection and RB allocation in carrier-aggregated 5G networks. They examined meeting the latency requirements of the 5G network and average user throughput while limiting the frequency of CC activations and deactivations. Their study presented two methods, QAP and QAP-ACDC, for the simultaneous assignment of RBs and CCs to users in downlink transmission while taking into consideration their Channel Quality Index (CQI) and Quality of Service requirements. Their findings show that both recommended techniques boost throughput and delay performance and would considerably help 5G networks achieve their essential throughput and delay requirements.

Under the UE energy consumption limitation, an upper bound on 5G CA performance was supplied by [126]. Their objective was to choose CCs and allocate Resource Blocks (RBs) so that total user throughput was maximized, while user power consumption was minimized and QoS criteria were met. They provided a multi-objective optimization problem and represented UE throughput and power consumption using CC and RB indicators. They tackled the throughput maximization problem using the maximum-largest weighted delay first (M-LWDF) method and prioritized users that demanded reduced delay and packet loss rate objectives. Their objective was to choose CCs and assign RBs to maximize total user throughput while minimizing user power consumption and meeting QoS criteria. They offered a multi-objective optimization issue and quantified UE throughput and power consumption using CC and RB metrics. They used the maximum-largest weighted delay first (M-LWDF) algorithm to address the throughput maximization problem, giving precedence to users that demanded reduced delay and packet loss rate objectives.

The NOMA approach may also be used with CA to reportedly improve customers' data rates and transmission capacity up to 100 MHz, subject to spectrum availability and user compatibility. A user pairing based on the NOMA approach and coupled with CA was investigated to increase system performance [127]. The number of aggregated CCs was determined to allow for both the anticipated high traffic loads in certain of the CCs and the inherent channel variety of the NOMA concept. A CC was created for the macro-BS to offer coverage for the macro-cell, and another CC was created for the tiny cells to provide specialized coverage. Thus, aggregated CCs shared by macro-BS and small cells were supported by the same CA structure, boosting system throughput. According to their findings, the CA-NOMA method significantly improved the total rate and EE, thereby improving the predicted peak user throughput for 5G networks.

In Konstantinou et al. [128], an mmWave analog RoF link was employed to demonstrate the transmission of carrier aggregated OFDM signals in accordance with the 5G new radio numerology. The number of aggregated CCs was determined to allow for both the anticipated high traffic loads in certain of the CCs and the intrinsic channel variety of the NOMA concept. A CC was developed for the macro-BS to provide coverage for the macro-cell, and another CC was created to offer specialized coverage using the tiny cells. Thus, macro-BS and small cells shared aggregated CCs supported by the same CA structure, boosting system throughput. The CA-NOMA method showed great improvement in terms of total rate and EE, thereby enhancing the peak user throughput projected for 5G networks, according to the findings in the paper.

5.2. Spectrum Sharing in 5G

The 5G NR networks need small cells and should be highly populated to operate. These networks might share a frequency band with other services that operate on distinct bands. The current spectrum-sharing plans will be effectively used as 5G is developed to fulfill the requirements of relevant applications. A summary of a few spectrum-sharing plans that may be adopted for 5G technology is given as follows.

A. TV White Space: Frequencies for TV not used by authorized users are referred to as "white spaces". The FCC recommended sharing unused TV frequencies with authorized users and their low-powered equipment. The primary consumers are TV receivers, which are protected from interference and given higher transmission priority. Users who lack a license are secondary users. They have poor transmission priority and are not protected from interference from major users.

B. Licensed Shared Access (LSA): TVWS has a drawback in that it cannot deliver the necessary level of service to secondary users. Hence, it cannot completely address the issue of spectrum scarcity. A novel approach to spectrum sharing, known as the LSA, has been made available to mobile operators [129]. While the LSA sharing scheme protects new licensees from interference, allowing them to access the spectrum with predictable quality of service, Authorized Spectrum Access (ASA) allows spectrum owners (current owners of the underutilized spectrum) to grant a small number of mobile operators access to their underutilized spectrum. This benefits both the incumbent, who may be permitted to stay in the band longer and eventually receive financial compensation, and the LSA licensee, who may use an underutilized band at an inexpensive cost while the band cannot be cleared or rebuilt. The 2300–2400 MHz band was the first to be authorized for LSA in Europe [129].

C. Spectrum Access Sharing (SAS): The Spectrum Access System (SAS) was initially suggested in the United States, particularly for the 3550–3700 MHz band, as one of many projects aimed at providing more spectrum for mobile broadband [130]. In contrast to earlier sharing strategies, SAS employs a three-tier sharing structure that permits the use of the available spectrum by three different user categories: Federal users, Priority Access Licensed (PAL) users, and General Authorized Access (GAA) users. The Federal users are shielded from all types of interference and have full access to the spectrum. The PAL users are shielded from interference from all users except the Federal users and can utilize the spectrum only when the Federal users are not. Only opportunistic access to the spectrum is available to the GAA users as a result of their lowest priority, and they have no interference protection.

5.3. The 5G Research Groups

The following are some significant research organizations involved in the standardization of 5G technology.

A. METIS (Mobile and wireless communications Enablers for Twenty-twenty (2020) Information Society)—METIS concentrated on RAN design, creating an air interface that analyses peak data rates, traffic load by area, traffic volume per user, and real client data rates. In February 2015, METIS released a study in which they constructed an RAN architecture with simulation results. They created an air interface that analyses data rates on the basis of peak hours, traffic load by area, user traffic volume, and precise client data rates. They were able to obtain an RAN latency of less than one millisecond [9,131,132]. They also used multiple RAN models and traffic flow in a range of locations, including colleges, malls, stadiums, and businesses.

B. The 5G PPP (5G Infrastructure Public–Private Partnership)—The fifth-generation infrastructure public–private partnership project is a collaboration between two entities (European Commission and the European ICT industry). Over the next decade, 5G-PPP will deliver numerous standardized designs, solutions, and innovations for next-generation mobile networks. The primary purpose of 5G-PPP is for the European Commission to apply this research to education, smart cities, intelligent transportation, entertainment, e-health, and media [9,131,132].

C. The 5GNOW (5th Generation Non-Orthogonal Waveforms for asynchronous signaling)—5GNOW is working on network modulation and multiplexing techniques for the next generation. The visible waveform communication of 5GNOW is ultra reliable and offers ultra-low latency. The 5GNOWs also employ the short-term Fourier transform (STFT) to gather signal time and frequency plane information [9,131,132].

D. EMPhAtiC (Enhanced Multicarrier Technology for Professional Ad Hoc and Cell-Based Communications)—EMPhAtiC is working on asynchronous secure communication systems using a configurable filter bank multi-hop transmission through MIMO. They have recently demonstrated an MIMO-based trans-receiver approach for Filter Bank Multi-Carrier in frequency selective channels (FBMC) [9,131,132].

E. NEWCOM (Network of Excellence in Wireless Communications)—NEWCOM's research and development efforts are focused on wireless energy efficiency, channel efficiency, and multi-hop communication. They are actively working on cloud RAN, mobile broadband, local and distributed antenna systems, and multi-hop communication for 5G networks. Finally, their research shows that the baseband is handled through the use of a QAM modulation architecture, system bandwidth, and resource block [9,131,132].

F. NYU New York University Wireless—NYU Wireless is a research institution for wireless communication, sensing, networking, and device development. Recent NYU research focuses on developing smaller, lighter antennas with directional beamforming to allow dependable wireless communication [9,131,132].

G. The 5GIC 5G Innovation Centre—5GIC is a UK-based high-speed wireless communication research organization. In their most recent investigation, they attained 1Tbps speed in point-to-point wireless communication. Their major objective is to provide ultra-low latency application services [9,131,132].

H. ETRI (Electronics and Telecommunication Research Institute)—ETRI is a Korean research group that focuses on 5G network stability, device-to-device communication, and the MHN protocol stack [9,131,132].

5.4. Blockchain-Based Security in 5G Network

Security of the 5G network is a top concern for the communication system since the network is dynamic and radio frequency signals are transmitted on-air without adequate protection. An attacker who is close to the broadcast signal can easily take advantage of this and carry out several malicious activities, including stealing sensitive data, listening in on conversations, modifying the signal, or even disrupting the entire connection. Apart from the inherent weakness of wireless communication, the 5G network has security issues due to the numerous application and technologies it supports, as these technologies and applications are vulnerable to several attacks, such as Man-in-the-Middle (MITM) attacks, eavesdropping attacks, hijacking attacks, malware attacks, etc. [133,134]. This has drawn the attention and interest of several authors who have tried to design and develop various security algorithms and schemes to defend against these attacks in the 5G network over the years. Blockchain technology is a widely utilized technology for providing security in the 5G network. It refers to a chain of blocks where each block contains some verified records, and all blocks are connected using their crypto-hashes [135]. This technology is also well-known in bitcoin cryptocurrency transactions. Blockchain technology is a decentralized, invariable, and encrypted ledger that guarantees trust between untrustworthy parties without the use of a centralized third party. This decentralized framework allows efficient and reliable blockchain operations, with fraud protection and no single point-of-failure weaknesses [136]. Furthermore, blockchain technology has several security benefits, including providing full control of information when transmitted over an untrusted or unprotected network, improving the performance of the overall system, as it does not require any centralized system to function, and simplifying the network. Figure 12 depicts the integration of blockchain and the 5G network.

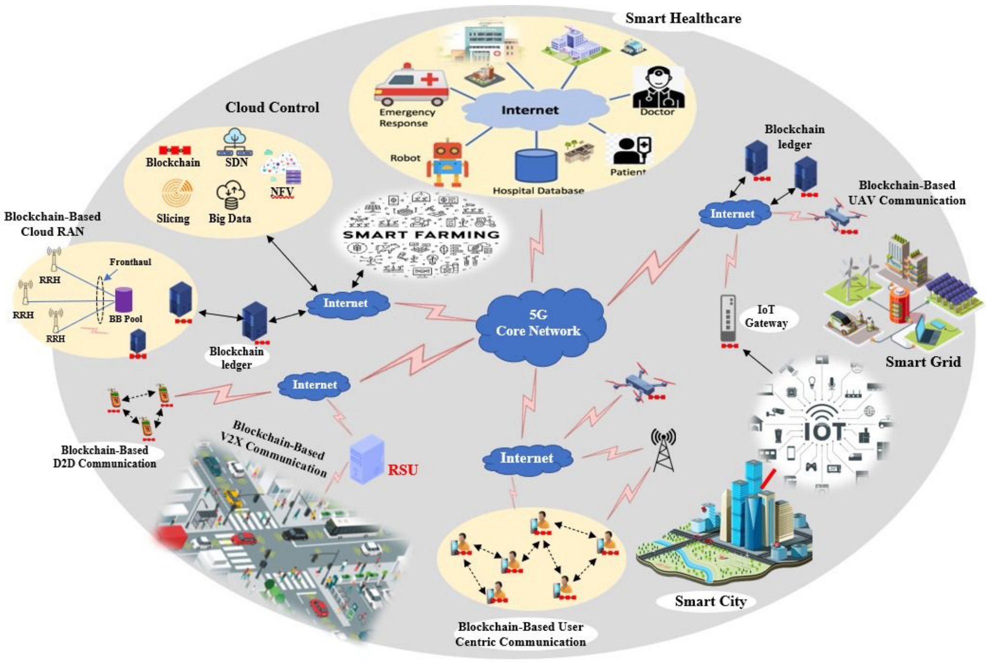

Figure 12. Integration of 5G Network and Blockchain Technology for Improved Security.

5.5. Integration of Non-Terrestrial Networks (NTNs) with 5G

This section will discuss the NTN-5G integration overview, standardization, architectures, and use cases.

5.5.1. Overview of the NTN

The non-terrestrial satellite network (NTSN) is a mega satellite constellation network that guarantees global network coverage with a high data rate, better security, and low latency communication, allowing it to provide more benefits over the terrestrial network. These capabilities can compensate for the drawbacks of conventional mobile communication [137,138]. NTN operates through a spaceborne vehicle, such as the geostationary earth orbit (GEO), medium earth orbit (MEO), and low earth orbit (LEO) satellites. Unmanned aerial vehicles (UAVs) and high-altitude platforms (HAPs) may also be employed by NTN to provide coverage to areas where the conventional terrestrial network could not ordinarily reach [139]. The development of non-terrestrial networks, driven by low earth orbit (LEO) mega-constellations, has rapidly grown in recent years [140]. These networks can potentially revolutionize how we communicate, providing faster and more reliable connectivity to remote and underserved areas. The use of LEO mega-constellations in non-terrestrial networks is expected to increase in the coming years due to the advantages they offer in terms of low latency and high throughput and their ability to provide global coverage [141–143]. The use of advanced technologies, such as RIS and the integration of non-terrestrial networks with IoT, is key to the success of these networks and, when employed, will significantly improve the 5G signal quality and reduce the impact of atmospheric conditions on the transmission of data. Satellite communications have received much attention from researchers and industry due to the quick advancement of communication technologies. Particularly since the launch of numerous commercial satellite constellations, such as Starlink and OneWeb, various satellite technology-related concerns have taken center stage in 5G communications research [144].

5.5.2. The 3GPP NTN Standardization

Work on the NR NTN by the 3GPP began in 2017 with Release 15 (Rel-15) in June 2018 and was centered on developing channel models and deployment scenarios for the 5G NTN [145]. Rel-15 concentrated on two main goals: the first was to choose a few typical NTN deployment scenarios and reach a consensus on important factors, including architecture, orbital height, and frequency bands, while the second focused on developing NTN channel models based on terrestrial 3GPP channel models. Key outcomes of the Rel-15 include the recommendation of S- and Ka-bands as NTN frequency ranges and the development of channel models that support urban, suburban, and rural scenarios. On completion of Rel-15, approaches to 5G NR adaptation for NTN were studied by 3GPP in Release 16 (Rel-16) [146], with a major goal of determining the minimum requirement for successful integration of 5G NR with NTN. The study reports from Rel-16 led to the initiation of Release 17 (Rel-17) by the 3GPP. Unlike the earlier releases, the main aim of Rel-17 was to define necessary improvements for LEO and GEO-enabled NTNs while providing complete support for air-to-ground and HAPS networks. The latest study on 5G NR and NTN integration is contained in Release 18 of the 3GPP for 5G NR and was released in December 2021. It aims to upgrade 5G NR by incorporating more sophisticated technologies, such as AI and ML [147,148].

5.5.3. NTN Architectures

The adoption of NTN technology would significantly enhance 5G communication services when combined with the current terrestrial communication architecture. In a typical terrestrial cellular radio access network (RAN), standard communication components, such as the BS, UE, core network, and data network, are crucial for successful service delivery [149]. While the core network is charged with the responsibilities such as mobility management and session management, the data network focuses more on ensuring successful data transfer from one network access point to the other. These various network components play a complementary role in the total communication process. Thus, failure of a particular component may render the entire communication process useless. For typical NTN networks, the network architecture has been designed to provide enough redundancy to avoid network failures. Therefore, the integration of NTN components with the existing terrestrial infrastructures will play a crucial role in transforming communication processes. NTN integration can adopt either the physical (PHY) or network (NET) layer integration approach. While the former adopts existing terrestrial components for the NTN integration, the latter employs new radio access technologies (RATs). The NTN architecture may be any of the underlisted, depending on the non-terrestrial (NT) positioning [148,149].

a. NT platform as a user: This architecture uses terrestrial infrastructure from an existing network to provide service for the NTN platform. Moreover, it might designate other satellites at higher altitudes to service satellites as users. Since the space satellites are served by the ground station (GS), this design enables communication to occur independently of ground stations, lowering the potential roundtrip delay.
b. NT platform as a relay: Here, there may be two possibilities. The NTN platform can be used to provide backhauling services by acting as the link between the BS and the core network, which is typically secured by fiber optics. The NTN platform can alternatively serve as a relay in the connection between users on the ground and BS, thus providing direct access connectivity.
c. NT platform as a BS: The BS functionalities can be incorporated into the flying component in this approach. This method is applicable only to scenarios where the NTN platform is equipped with a regenerative payload with enough processing capabilities.
d. In addition to the three architecture models mentioned above, mixed architectures may combine several NT platforms to serve various functions [142]. A diagram showing the general architecture of NTN is presented in Figure 13.

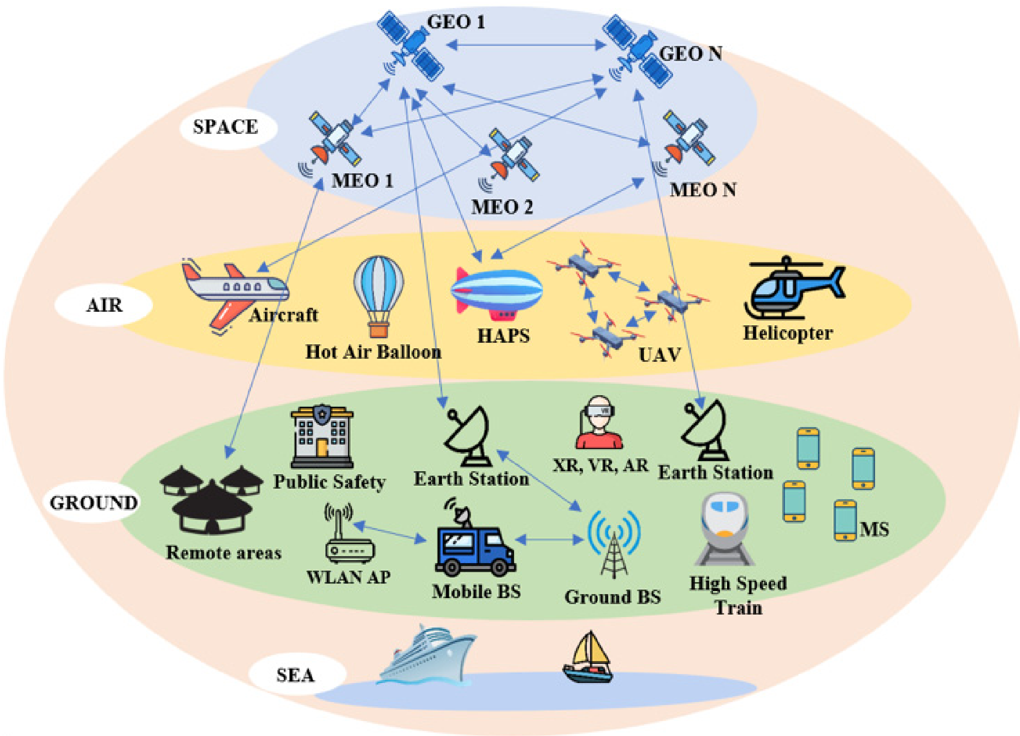

Figure 13. General Architecture of NTN.

5.5.4. NTN Use Cases

Various use case scenarios for satellite-based NTNs have been discussed by the 3GPP systems aspects workgroup in the study item on Satellite Access in 5G [146]. The three main categories of use cases identified for 5G satellite-based NTNs are discussed below.

a. Service Continuity: This use case applies primarily to applications that make use of satellites' vast coverage capabilities, such as multicasting or broadcasting. It is made to offer a network for situations when terrestrial 5G networks alone are unable to give enough 5G coverage.
b. Service Ubiquity: This use case is intended for unserved or underserved areas with limited access to terrestrial networks. Examples of IoT use cases that come under this category include smart agriculture and emergency medical services.
c. Service Scalability: This is for use cases where multicasting or broadcasting a specific piece of content over a limited geographic area while utilizing the wide satellite coverage area is advantageous. Applications that rely on UHD services are suitable examples for this use case.

5.5.5. NTN Platforms

NTN architecture can use varying deployment options, depending on the type of NTN platform involved. Spaceborne and Airborne platforms are the two basic categories of platforms used by the NTN. Parameters such as platform altitude, orbit, and beam footprint size are the basic factors determining the classification of the platforms [150]. In Table 9, we give a summary of the classifications of the NTN platforms.

Table 9. NTN platform classifications [151,152].

Platform	Type	Altitude Range	Orbit	Beam Footprint Size
GEO satellites	Spaceborne	35,786 km	Fixed position based on elevation, with respect to a given point on Earth	2000–3500 km
MEO satellites	Spaceborne	7000–25,000 km	Circular around Earth	100–1000 km
LEO satellites	Spaceborne	300–1500 km	Circular around Earth	100–1000 km
UAVs	Airborne	8–50 km	Fixed position based on elevation, with respect to a given point on Earth	5–200 km
HAPs	Airborne	20 km	Fixed position based on elevation, with respect to a given point on Earth	5–200 km

6. The 5G Spectrum Standardization

The International Telecommunication Union (ITU) was founded in 1865 as a result of a global agreement between the private and public sectors on the visibility of enabling the connection of communication networks, allocation of radio frequency bands, and development of international technical communication standards [56]. The main responsibility of the ITU is to create standards for unified communications that will allow networks and technologies to be integrated globally, thus enabling unrestricted access to telecommunications services. In relation to IMT systems, the ITU regulates each element of the radio communication system. The ITU is also in charge of harmonizing and standardizing the frequency band requirements for mobile communication technologies to promote cross-platform interoperability between current and emerging technologies. The ITU oversees, assesses, and develops the requirements for 5G technology [153].

The ITU Radio regulations outline the spectrum assignments that ITU-R has been working on over the years for various applications and other services. There are several spectrums identified for IMT systems. A list of these bands and the corresponding radio communication conference that approved them are contained in [154]. Although some preferences are being established, 5G theoretically can be deployed in any of the specified bands.

The USA is willing to use the 3.5 GHz (3550–3700 MHz) shared band as well as the 600 MHz licensed spectrum (617–652/663–698 MHz). The radio frequency below 1 GHz that Europe has selected for 5G is the 700 MHz band (694–790 MHz), but the leading pioneering 5G spectrum should be 3.4–3.8 GHz. To enable more downlinks, the 1.5 GHz band (1427–1452/1492–1518 MHz) is also being considered [12,155]. Other nations are investigating the optimal band to roll out their 5G services. Japan is considering the frequencies of 3600–4200 MHz and 4400–4900 MHz for the testing 5G deployment. Nigeria is considering the 3500 MHz and 26,000 MHz frequencies, while in China, the frequencies being considered are the 3300–3600 MHz and 4800–4990 MHz bands [64,123,154].

Due to the steadily increasing data traffic, more spectrum resources are required to support upcoming mobile communication networks. Furthermore, it is significant to remember that each nation will have different specifications for its national spectrum. Therefore, this section covers discussions on the different spectrum allocations and assignments for the 5G network and the sub-6GHz and above-6GHz frequencies. Furthermore, the worldwide trials and the different deployment modes of the 5G network are presented.

6.1. Spectrum Allocation and Assignment

A sufficient radio spectrum in the low-, mid-, and high-frequency bands is essential for the deployment of a 5G network to support the many use cases and applications. The 5G standard separates two carrier frequency ranges known as FR1 (sub-6GHz with TDD and FDD), and FR2 (mmWave band, 23–53 GHz with TDD) [155,156]. While some of these frequencies will be allocated particularly for the deployment of the 5G network, other frequencies will need to be obtained from existing communication services. In [154], the comprehensive list of available frequency ranges for the 5G FR1 and FR2 frequencies are presented, where frequencies in FR1 support TDD, FDD, and Supplemental Downlink/Uplink (SDL UL/DL); frequencies in FR2 support only TDD, which uses the same frequencies for transmission from both the device and the base station but are coordinated to transmit at different times to reduce interference. By contrast, with FDD, the base station and the device each transmit data using a separate frequency.

6.2. The FR1 Band

In addition to supporting wide areas and indoor/outdoor coverage, 5G also offers high data rates. As a result, the spectrum below 6 GHz is critical to the 5G solution [123,157]. Over 1200 MHz of the spectrum in Europe's frequency range between 694 MHz and 3800 MHz has already been harmonized for mobile broadband. The key frequency band appropriate for the launch of 5G in Europe even before 2020 is in the 3400–3800 MHz range, which has been harmonized for mobile networks and has up to 400 MHz of the continuous spectrum. This spectrum could allow Europe to be a global leader in 5G or pre-5G deployment [65].

6.3. The FR2 Band

High data speeds expected from 5G will require substantially wider bandwidths than in the past. Only higher frequency bands (above 6 GHz) have those extraordinarily high data rates. In order to provide faster data speeds and lower latency, it is projected that new wireless solutions at higher frequencies—millimeter wave bands—would be introduced. To fulfill all of the 5G performance goals, such as multi-gigabit-per-second data rates, frequency bands even over 24 GHz must be implemented. Very low latency has implications for millimeter wave deployments because of their small cell sizes and highly directional antennas [64,123].

6.4. Worldwide 5G Trials

Commercial 5G networks have already begun operating in several nations worldwide. Other nations that have not achieved full implementation have likewise advanced in their deployment of the network. Table 10 lists the regions and operators for each of the current global 5G deployments. However, virtually every Asian country has also invested in 5G technology. The first 5G network was deployed in South Korea, and it is projected that the country will continue to lead the way in the adoption of the technology. Other nations have likewise advanced in their deployment of 5G technology recently.

Table 10. Global 5G Deployment Statistics (source: GSA).

Region	Country	Sub-Region	Operator	Status	Launch Date	Freq. MHz
AFRICA	Nigeria	West Africa	MTN	Live	Aug. 2022	3500
	South Africa	Southern Africa	Vodacom	Live	May 2020	3500
ASIA	Saudi Arabia	Western Asia	Zain	Live	Oct. 2019	
	Hong Kong; SAR China	Eastern Asia	3 (CK Hutchison)	Live	Apr. 2020	
	Hong Kong; SAR China	Eastern Asia	China Mobile	Live	Apr. 2020	
	Japan	Eastern Asia	SoftBank	Live	Mar. 2020	2500
	Japan	Eastern Asia	KDDI	Live	Mar. 2020	
	Japan	Eastern Asia	NTT DOCOMO	Live	Mar. 2020	3700/450 0/28,000
	Hong Kong; SAR China	Eastern Asia	csl (HKT)	Live	Apr. 2020	3300
	Thailand	Southeastern Asia	TrueMoveH (True Corporation)	Live	Mar. 2020	2600
	Thailand	Southeastern Asia	Advanced Wireless Network (AIS)	Live	Mar. 2020	2600
	Saudi Arabia	Western Asia	STC	Live	Sep. 2019	3500
	Philippines	Southeastern Asia	Globe Telecom	Live	Feb. 2020	
	Qatar	Western Asia	Ooredoo	Live	Jan. 2020	
	China	Eastern Asia	China Unicom	Live	Oct. 2019	
	China	Eastern Asia	China Mobile	Live	Oct. 2019	
	China	Eastern Asia	China Telecom	Live	Oct. 2019	
	Qatar	Western Asia	Vodafone	Live	Aug. 2019	
	Maldives	Southern Asia	Dhiraagu (Batelco)	Live	Aug. 2019	
AMERICA	United States of America	Northern America	GCI	Live	Apr. 2020	
	Canada	Northern America	Rogers	Live	Mar. 2020	
	United States of America	Northern America	T-Mobile (Deutsche Telekom)	Live	Apr. 2020	
	United States America	Northern America	US Cellular (TDS)	Live	Mar. 2020	
EUROPE	Netherlands	Western Europe	Vodafone-Ziggo (Liberty Global/Vodafone) (Liberty Global/Vodacom)	Live	Apr. 2020	1800
	Hungary	Eastern Europe	Magyar Telekom	Live	Apr. 2020	3600
	Belgium	Western Europe	Proximus	Live	Apr. 2020	
	Norway	Northern Europe	Telenor	Live	Mar. 2020	
	United Kingdom	Northern Europe	3 (CK Hutchison)	Live	Feb. 2020	
	Finland	Northern Europe	DNA	Live	Jan. 2020	
	Austria	Western Europe	A1 Telekom	Live	Jan. 2020	3500
	Latvia	Northern Europe	Tele2	Live	Jan. 2020	3500
	Romania	Eastern Europe	Orange	Like	Nov. 2019	
	Ireland	Northern Europe	eir	Live	Oct. 2019	
	United Kingdom	Northern Europe	O2 (Telefonica)	Live	Oct. 2019	
	Hungary	Eastern Europe	Vodafone	Live	Oct. 2019	3600
	Finland	Northern Europe	Telia	Live	Oct. 2019	4500
	Austria	Western Europe	3 (CK Hutchison)	Live	Oct. 2019	
	Ireland	Northern Europe	Vodafone	Live	Aug. 2019	

6.5. The 5G Deployment Modes

There are two ways to implement 5G. The first is the Standalone 5G deployment paradigm, offering services over an entire 5G network. The second mode, Non-Standalone, uses a combination of 5G and LTE architectures to deliver services [5].

A. Non-Standalone (NSA): The Non-Standalone mode of 5G NR deployment relies on the 4G core network for control plane operations, such as session management, resource allocation, handover management, authentication, and policy management. This deployment option provides 5G services without an end-to-end 5G network instead of relying on 4G system components. Telecom companies frequently use this method for the rapid and cost-effective deployment of 5G networks. Deploying a 5G network in NSA mode can provide faster data speeds but cannot guarantee all of the 5G objectives. However, with the assistance of an existing 4G network, operators can implement 5G, promoting early adoption of the technology, which is why the 3GPP released a preliminary set of NSA requirements before the full 5G standard was released. A cell in the NSA approach performs the control plane activities, while the user plane connection is provided jointly by both the LTE eNodeB and the 5G gNodeB [64,158]. NSA architecture will allow mobile operators to start 5G deployment since the 4G infrastructures can be retained for deployment and, thus, reduce network operation time. The cost of network deployment will also be reduced since operators can rely on existing 4G infrastructures. However, it is important to note that the NSA design is incapable of matching the exceptional performance of 5G networks in terms of speed, low latency, high data rate, and other factors.

B. Standalone (SA): The 5G NR Standalone mode differentiates between LTE and 5G networks by defining a separate core and radio access network for each network. This enables the true realization of 5G goals and end-to-end 5G connectivity. A simpler core network with lower operating costs is possible with 5G. The ability to arrange different types of UEs in separate network slices, each with a different QoS and set of rules, is a new feature in the 5G core network when compared with the 4G core network. Because UEs with lower resource requirements can be placed on a separate network slice, systems with the same capacity can handle more UEs more effectively than if a single policy was used for all UE types. This prevents the allocation of unnecessary resources. This is especially helpful in facilitating significant IoT installations. Since most IoT devices are sensors that do not need very low latency or high data rates, these UEs can be placed in a different network slice. Critical Internet of Things deployments can be placed in a different network slice with low latency [159]. The SA deployment method ensures operators can achieve the highest level of performance promised by 5G implementation. The revolutionary nature of 5G is a result of the fast data transfer rates and extremely low latency it offers, among many other enhancements. This mode was created to function on the 5G FR2 frequency since the entire SA architecture is made up of 5G infrastructures. This will ensure the 5G network aimed at extremely low latency and large data speeds is achieved. Huge infrastructure costs associated with the SA roll-out are a significant obstacle since telecommunication service providers would need to completely redesign their current LTE networks.

6.6. Application and Device Benchmarking in 5G Networks

In a typical 5G network, application developers and device manufacturers should be able to test and benchmark new mobile applications, devices, and services. A critical aspect of the mobile communications market is to guarantee the correct and efficient behavior of dense applications and massive devices to satisfy the requirements of end users. Although these mobile devices have been standardized, there is no adequate consensus on the benchmarking or testing methodologies at the application level. Thus, the need to identify reference deployment scenarios and the definition of new KPIs and QoE metrics becomes imperative.

It is worthwhile considering three distinct areas for testing and benchmarking. These include applications, devices, and mobile network operators. Interestingly, Small and Medium Enterprises (SMEs) provide these applications and often find accessing various testing processes in real-time wireless networks difficult. Another critical challenge for SMEs is understanding the requirements of standardized testing schemes and their associated products. Unfortunately, the enormous testing costs and the need for technical expertise often discourage SMEs from conducting robust tests.

A typical testbed scenario is shown in Figure 14. The architecture comprises the Orbit Management Framework (OMF), Orbit Measurement Library (OML), and OMF Experiment Description Language (OEDL). The OMF controls the experimental execution in testbeds. The OEDL technically describes the execution of an experiment and specifies the results in readable formats. Also specified is the Experiment Controller (EC) that interprets and orchestrates the OEDL scripts. Finally, the Resource Controller (RC) manages each resource in the testbed, and there are RCs for managing smartphones, among others.

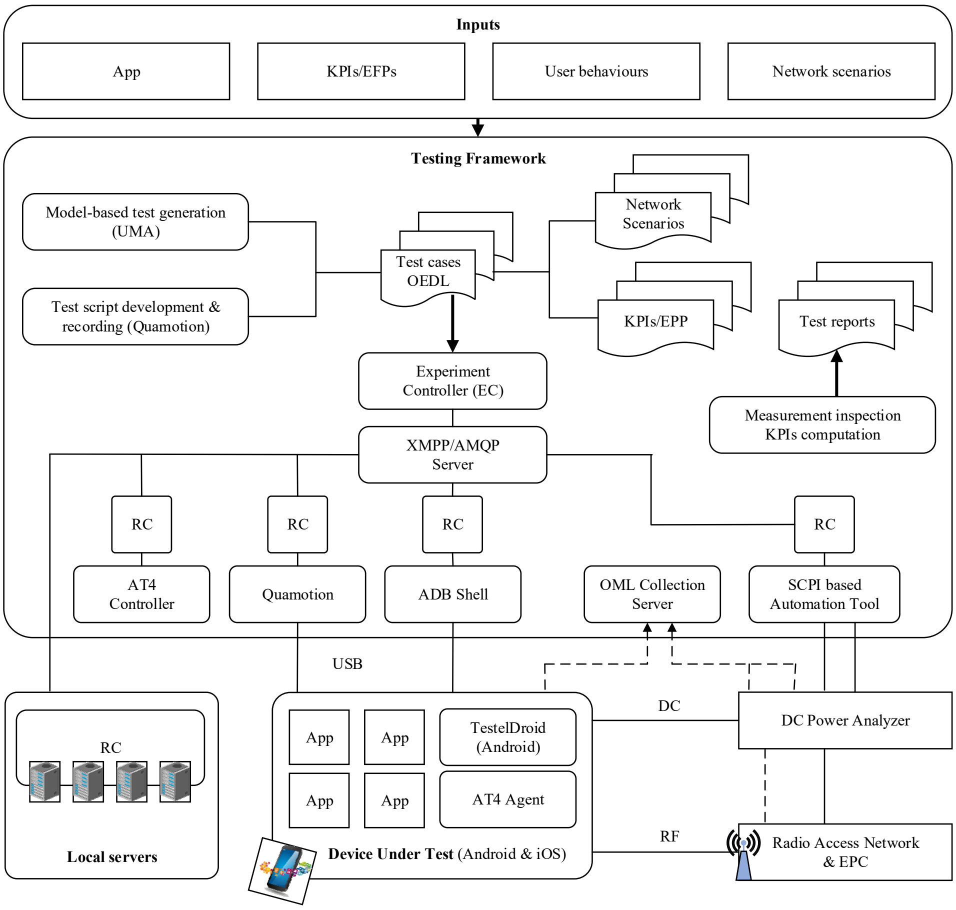

Figure 14. 5G Network Testbed and Benchmarking Scenario.

Last, the Advanced Message Queuing Protocol (AMQP) manages communication between the EC and RCs and measures data obtained through the OML. Finally, the test automation platform manages the DC power analyzer and the eNodeB emulator for design verification and signaling testing. In comparison, the DC Power Analyser helps to characterize power consumption in mobile devices.

7. 5G Radio Propagation Mechanisms

This section presents and discusses the various propagation characteristics of the FR1 and FR2 as well as the atmosphere-induced attenuation. Furthermore, the 5G path loss prediction models, the 5G models, and the 5G channel modeling are discussed.

7.1. Propagation Characteristics

The identified bands for the deployment and execution of IMT-2020 and beyond systems are the microwave and millimeter wave bands (i.e., 0.5–100 GHz). The bands are divided into FR1 and FR2 frequency ranges, with each band having unique benefits and applicability. While the FR2 (24.25 GHz–52.6 GHz) band is ideal for short-range communications and data rate delivery, the FR1 (410 MHz–7.125 GHz) bands are suitable for communications via conventional cellular mobile communication lines. FR 2 band transmissions cannot travel more than a few miles or easily pass through structures, in contrast to FR 1 band signals. Instead, FR2 bands can pass through extremely crowded communication lines, ensuring effective spectrum usage [160,161]. Since mmWave will use higher gain antennas to avoid route loss, it will be necessary to take advantage of and quickly react to the spatial dynamics of the wireless channel [72]. As they have a crucial impact on the architecture of the 5G system, their propagation characteristics need to be properly taken into account for effective propagation at these bands [162,163]. However, some additional loss variables, including rain, vapor, and gaseous losses, are unavoidable in mmWave networks.

A. Reflection: When an electromagnetic wave in motion collides with an impediment greater than its wavelength, reflection occurs. A traveling wave may be hampered by natural obstacles, such as the reflection of the earth's surface, structures, and walls.
B. Diffraction: This happens when the wave's tip encounters a solid barrier or a sharp object. As a result, the traveling wave will bend around the obstacle's tip, thus altering its course of propagation.
C. Scattering: This can be seen when a radio wave that is propagating encounters a rough surface or a very small body whose size is of the order of the radio signal wavelength. Similar to the physical concept of diffraction, energy from a transmitter is emitted in numerous directions when scattering takes place [164,165].

7.2. Atmospheric Gaseous Losses/Atmospheric Attenuation

When signal propagation at the millimeter waves passes through the atmosphere, they get absorbed by water vapor, oxygen, and other gaseous constituents in the atmosphere, thus attenuating the received signal [166].

A. Rain losses: Since radio wavelengths and droplets are essentially the same size, rain also attenuates mmWave propagation. As a result, the signal quality is affected when the radio waves are scattered as they encounter raindrops [167].
B. Foliage losses/Vegetation attenuation: Foliage losses and reduced vegetation foliage losses at FR2 frequencies are very damaging, in contrast to the microwave, where they have little impact. Since millimeter waves are far more susceptible to attenuation by foliage, this sensitivity typically grows as the signal's route through the foliage is extended.
C. Free-space path loss: Path loss occurs when clear routes are used for communication between the transmitter and receiver. Although mmWave has been said to have a substantial free-space path loss, studies have shown that this is only true if the gain of the mmWave antenna is considered to be frequency-independent [123,168]. When the antenna area is constant at one link end, path loss becomes frequency-independent, and when the antenna area is constant at both link ends, path loss reduces since higher frequencies enable higher antenna gain for a constant area.
D. Outdoor-to-indoor penetration: Higher frequencies result in greater attenuation of wall and window penetration. Mobile network users are more likely to be found indoors. Steel concretes, brick buildings, and energy-efficient windows all have attenuation values between 20 and 40 dB, whereas post and dry-wall dwellings have a value of less than 10 dB [169,170]. Both attenuation and penetration loss increase as the carrier frequency increases. In [170], the average attenuation and penetration loss of ceiling, clear glass, drywall, and plywood were plotted for 28, 39,120, and 144 GHz.

As presented in Figure 15, their result showed a clear increase in attenuation and penetration loss with an increase in frequency.

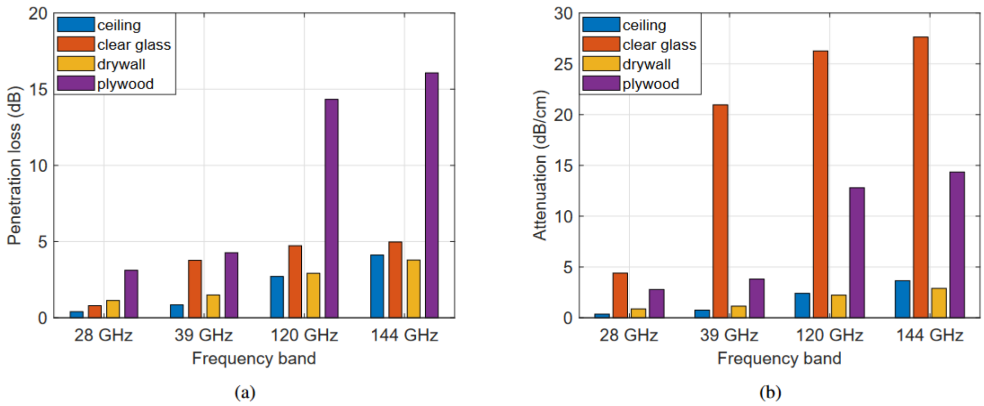

Figure 15. A graph showing the results of (**a**) average penetration loss and (**b**) average attenuation for ceiling, clear glass, drywall, and plywood at 28, 39, 120, and 144 GHz. The figure was reproduced from a paper [170] titled: Sub-Terahertz and mmWave penetration loss measurements for indoor environments; published in the 2021 IEEE International Conference on Communications Workshops (ICC Workshops).

7.3. The 5G Path loss Prediction Modelling Approaches

There are several path loss prediction models applicable to 5G. The common single-frequency and multi-frequency models are discussed in this section.

7.3.1. Single-Frequency Models

A. Close-In (CI) Model

The CI model equation for electromagnetic wave propagation is given by [171] in Equation (5):

$$PL^{CI}(f,l) = FSPL(f,1\text{ m}) + 10n\log_{10}(l) + X_{\sigma}^{CI}[\text{dB}]\text{for}l \geq 1\text{ m} \quad (5)$$

where X_{σ}^{CI} denotes a Gaussian random variable described by the standard deviation σ^{CI}(dB), and the random variable has a mean value of zero ($\mu = 0$).

The free-space path loss is the loss with a reference distance of 1 m, as shown in Equation (6)

$$(FSPL)(f,1\text{ m}) = 10\log_{10}\left(\frac{4\pi f}{c}\right)^2 \quad (6)$$

where n is the path loss exponent (PLE).

Equation (5) can be arranged using the MMSE-based optimization technique to determine the optimum n as given in (7):

$$X_{\sigma}^{CI} = PL^{CI}(f,l)[\text{dB}] - FSPL(f,1\text{ m}) - 10n\log_{10}(l);\text{for}l \geq 1\text{ m} \quad (7)$$

Assuming that $K = PL^{CI}(f,l)[\text{dB}] - FSPL(f,1\text{ m})$ and $P = 10\log_{10}(l)$, Equation (5) can then be written as (8)

$$\sigma^{CI} = \sqrt{\frac{\sum(X_{\sigma}^{CI})^2}{D}} = \sqrt{\frac{\sum(K-nP)^2}{D}} \quad (8)$$

By using the MMSE, the standard deviation of the shadow factor (SF) is calculated using (9):

$$\sigma^{CI} = \sqrt{\frac{\sum(X_{\sigma}^{CI})^2}{D}} = \sqrt{\frac{\sum(K-nP)^2}{D}} \quad (9)$$

where D represents the Tx–Rx separation distances, which define the number of different measurement distances recorded. The SF can be minimized with the standard deviation σ^{CI} when the term $\sum(K - nP)^2$ is reduced. To reduce $\sum(K - nP)^2$, the derivative about n should be zero as in Equation (10)

$$d\sum \frac{(K - nP)^2}{dn} = \sum 2P(nP - K) = 2\sum L(nL - F) = 2(n\sum L^2 - \sum LF) = 0 \quad (10)$$

Thus, from Equation (10), Equation (11) is derived:

$$n = \frac{\sum KP}{\sum P^2} \quad (11)$$

Therefore, the minimum SF standard variation for the CI model is given by (12)

$$\sigma^{CI}_{min}\sqrt{\frac{\sum(K - nP)^2}{D}} \quad (12)$$

B. Floating-Intercept (FI) Model

The FI approach is used by the Wireless World Initiative New Radio (WINNER) II and 3GPP for 5G path loss prediction [171].

$$PL^{FI}(l)[\text{dB}] = \alpha + 10\cdot\beta\log_{10}(l) + X^{FI}_{\sigma} \quad (13)$$

where the FI in dB is denoted by α, and it is equivalent to FSPL, while the slope of the line is denoted by β, which is similar to the path loss exponent (PLE).

$X^{FI}_{\sigma}(\mu,\ \sigma^{FI})$ denotes the Gaussian random variable with zero mean $(\mu = 0)$ and σ^{FI} represents the standard deviation that defines large-scale signal fluctuations about the mean path loss over the Tx–Rx spacing. Equation (13) requires two parameters, unlike the CI model, which requires just the parameter n. If we assume that G and P are defined in (14) and (15)

$$G = PL^{FI}(d)[\text{dB}] \quad (14)$$

and

$$P = 10log_{10}(d) \quad (15)$$

Then, the optimized lowest-level SF can then be expressed as (16):

$$X^{FI}_{\sigma} = G - \alpha - \beta P \quad (16)$$

and the SF standard deviation is given in (17):

$$\sigma^{FI} = \sqrt{\sum \frac{X^{FI^2}_{\sigma}}{D}} = \sqrt{\sum \frac{(G - \alpha - \beta P)^2}{D}} \quad (17)$$

As the minimum variation is anticipated for the term σ^{FI}, the expression $\sum(G - \alpha - \beta P)^2$, therefore, needs to be reduced; hence, its partial derivatives with respect to α and β return zero, as in (18) and (19):

$$\partial\sum(G - \alpha - \beta L)^2/\partial\alpha = \sum 2(\alpha + \beta P - G) = 2\left(D\alpha + \beta\sum P - \sum G\right) = 0 \quad (18)$$

$$\partial\sum \frac{(G - \alpha - \beta P)^2}{\partial\beta} = \sum 2L(\alpha + \beta P - G) = 2\left(\alpha\sum P + \beta\sum P^2 - \sum PG\right) = 0 \quad (19)$$

Equations (18) and (19) combined give (20) and (21):

$$D\alpha + \beta \sum P - \sum G = 0 \tag{20}$$

$$\alpha \sum P + \beta \sum P^2 - \sum PG = 0 \tag{21}$$

Combining (20) and (21) gives (22) and (23):

$$\alpha = \frac{\sum P \sum PG - \sum P^2 \sum G}{(\sum P)^2 - D \sum P^2} \tag{22}$$

$$\beta = \frac{\sum P \sum G - D \sum PG}{(\sum P)^2 - D \sum P^2} \tag{23}$$

then, the optimal standard deviation of the SF can be obtained by replacing α and β in (17) with (22) and (23), respectively. In the dB scale, the mean values of all vector elements can be determined directly [171].

7.3.2. Multi-Frequency Propagation

A multi-frequency propagation model is deemed necessary in closed-indoor environments after a 1 m distance from the transmitter due to the frequency-dependent loss that exists because of its surrounding environment [72]. The following are the main multi-frequency propagation models.

A. CIF Model

The frequency-dependent path loss exponent (CIF) can be added to the CI model, which uses the same free space path loss anchor at 1 m as the CI model. The path loss due to the CIF method is given by [171] in (24):

$$PL^{CIF}(f,d)[\text{dB}] = L(f, 1\text{ m}) + (n(1-n) + nbf/f_0)10.log(d/1\text{ m}) + S^{CIF}_{\mu,\sigma} \tag{24}$$

where d(m) denotes the Tx-Rx separation distance above 1 m, n is the PLE (in dB), $\sigma^{CIF} = \sqrt{\sum (S^{CIF}_{\mu,\sigma})^2/N} = \sqrt{\sum (F - Z(p+qf))^2/N}$ represents the Gaussian random variable with a zero mean and standard deviation σ (in dB), and b denotes the path loss slope known as the optimization parameter. L(1 m) is the free-space loss (FPL) at a distance of 1 m, and f_c is the center frequency given in (25)

$$L_0(\text{dB}) = 20log\left(\frac{4\pi d_o}{\lambda}\right) = 32.4 + 20logf_c(\text{GHz}) \tag{25}$$

where f(GHz) is the operating carrier frequency, and f_o is the minimum investigated frequency of operating frequencies. The frequency f_0 can be calculated as (26):

$$f_0 = \frac{\sum_{k=1}^{K} f_k N_k}{\sum_{k=1}^{K} N_k} \tag{26}$$

where f_0 is the weighted frequency average of all measured frequencies for individual scenarios, which can be obtained by summing up all frequencies, N_k is the sum of recorded data at a certain frequency and antenna scenario, f_k is the corresponding frequency, and $\sum_{k=1}^{K} N_k$ is the sum of all measurements taken across all considered frequencies for a specific scenario and transmitter/receiver system.

CIF Method: MMSE-Based Parameters

From Equation (24), after changing sides of the equation, assuming Equations (27)–(30):

$$F = PL^{CIF}(f,d)[\text{dB}] - L(f, d_0) \tag{27}$$

$$Z = 10log\left(\frac{d}{d_0}\right) \quad (28)$$

$$p = n(1-b) \quad (29)$$

$$q = \frac{nb}{f_0} \quad (30)$$

Equation (31) is obtained:

$$\sigma^{ABG} = \sqrt{\sum \frac{X_\sigma^{ABG^2}}{D}} = \sqrt{\sum \frac{(A - \alpha L - \beta - \gamma R)^2}{D}} = F - Zp + qf \quad (31)$$

The SF standard deviation is given by (32):

$$\sigma^{CIF} = \sqrt{\sum (S_{\mu,\sigma}^{CIF})^2/N} = \sqrt{\sum (F - Z(p+qf))^2/N} \quad (32)$$

Minimizing σ^{CIF} means minimizing $\sum(F - Z(p+qf))^2$, which in turn results in its derivatives with respect to p and q becoming zero, yielding (33) and (34):

$$\partial \sum (F - Z(p+qf))^2/\partial p = \sum 2Z(pZ + qZf - F) = 2\left(p\sum Z^2 + q\sum Z^2 f - \sum ZF\right) = 0 \quad (33)$$

$$\partial \sum (F - Z(p+qf))^2/\partial p = \sum 2Z(pZ + qZf - F) = 2\left(p\sum Z^2 f + q\sum Z^2 f^2 - \sum ZFf\right) = 0 \quad (34)$$

Simplification and combination give (35) and (36):

$$p = \sum Z^2 f \sum ZFf - \frac{\sum Z^2 f^2 \sum ZF}{(\sum Z^2 f)^2} – \sum Z^2 \sum Z^2 f^2 \quad (35)$$

$$q = \sum Z^2 f \sum ZF - \frac{\sum Z^2 \sum ZFf}{(\sum Z^2 f)^2} - \sum Z^2 \sum Z^2 f^2 \quad (36)$$

The closed-loop solution of the assumed terms p and q was derived in Equations (35) and (36). Inserting p and q into Equation (30) yields the standard derivation of the shadow factor. By using the initial definition $p = n(1-b)$ and $q = \frac{nb}{f_0}$, the values of n and b can be computed.

B. ABG Model

To determine the propagation loss at various frequencies, the ABG model, which is a three-parameter multi-frequency model consisting of frequency- and distance-dependent terms can be exploited.

The ABG model equation is given by (37)

$$PL^{ABG}(f,d)[\text{dB}] = 10\alpha log_{10}\left(\frac{d}{d_0}\right) + \beta + 10\gamma log_{10}\left(\frac{f}{1\ \text{GHz}}\right) + X_\sigma^{ABG} \quad (37)$$

where α and γ are the link's path length and frequency components of path loss, respectively, f is the frequency in GHz, and β is a term with no physical significance.

The $X_\sigma^{ABG}(\mu, \sigma^{ABG})$ parameter is a Gaussian random variable that describes large-scale variations in the mean path loss between transmitter and receiver. Essentially, the ABG model is a multi-frequency extension of the FI model. It can be shown that when $\gamma = 0$ or 2 is used and deployed for a single frequency, it transforms into an FI model. The

MMSE-based optimization technique can be used to find the best values for the α, β, and γ coefficients.

If the ABG model is reduced to the CI, it will resemble the CI model in shape. If $\alpha = 20log(4\pi/c), \beta$ will reduce to PLE n, and γ will reduce to 2.

The values of the parameters obtained through the MMSE-based optimization can be calculated by assuming that in (37), Equations (38)–(40) hold:

$$A = PL^{ABG}(f,d)[\text{dB}] \tag{38}$$

$$L = 10log_{10}(d) \tag{39}$$

$$R = 10log_{10}(f) \tag{40}$$

while the SF is given by (41):

$$X_\sigma^{ABG} = A - \alpha L - \beta - \gamma R \tag{41}$$

and the SF standard deviation is (42):

$$\sigma^{ABG} = \sqrt{\sum \frac{X_\sigma^{ABG^2}}{D}} = \sqrt{\sum (A - \alpha L - \beta - \gamma R)^2 / D} \tag{42}$$

As the slightest variation is expected for the term σ^{ABG}, that is, the expression $\sum(A - \alpha L - \beta - \gamma R)^2$ is to be zero, this can be achieved through the partial derivatives of α and β and by setting γ with respect to zero as follows (43)–(45):

$$\frac{\partial \sum(A - \alpha L - \beta - \gamma R)^2}{\partial \alpha} = \sum 2L(\alpha D + \beta + \gamma R - A) = 2\left(\alpha \sum L^2 + \beta \sum L + \gamma \sum LR - \sum LA\right) = 0 \tag{43}$$

$$\frac{\partial \sum(A - \alpha L - \beta - \gamma R)^2}{\partial \beta} = \sum 2(\alpha L + \beta + \gamma R - A) = 2\alpha \sum L + D\beta\gamma \sum R - \sum A = 0 \tag{44}$$

$$\frac{\partial \sum(A - \alpha L - \beta - \gamma R)^2}{\partial \gamma} = \sum 2R(\alpha L + \beta + \gamma R - A) = 2\left(\alpha \sum LR + \beta \sum R + \gamma \sum R^2 - \sum RA\right) = 0 \tag{45}$$

From (43)–(45), it is clear that (46)–(48) hold:

$$\alpha \sum L^2 + \beta \sum L + \gamma \sum LR - \sum LA = 0 \tag{46}$$

$$\alpha \sum L + D\beta + \gamma \sum R - \sum A = 0 \tag{47}$$

$$\alpha \sum LR + \beta \sum R + \gamma \sum R^2 - \sum R = 0 \tag{48}$$

By solving the matrix in (49), the numeric values of α, β, and γ for the ABG model are as follows:

$$\begin{pmatrix} \alpha \\ \beta \\ \gamma \end{pmatrix} = \begin{pmatrix} \sum L^2 & \sum L & \sum LR \\ \sum L & D & \sum R \\ \sum LR & \sum R & \sum R^2 \end{pmatrix}^{-1} \begin{pmatrix} \sum LA \\ \sum A \\ \sum RA \end{pmatrix} \tag{49}$$

7.4. General 5G Models

As illustrated and explained below, there are up to nine general 5G models that have been created over time for various frequency bands.

A. COST 2100 Channel Model: The COST 2100 channel model, which focuses on frequencies less than 6 GHz band, was derived from the COST 259 channel model and the COST 273 channel models [27]. It categorizes clusters into three types, namely single-bounced clusters, local clusters, and twin clusters. The local clusters are close to the BS or MS, the single-bounced and twin clusters are far from the BS and MS, and the single clusters can be located using the delays and angular parameters. However, both sides must describe the twin clusters' locations.

B. QuaDRiGa: The QUAsi-Deterministic RadIo channel GenerAtor (QuaDRiGa) is a GBSM that evolved from the WINNER+ channel model and added many other enhancements. The most recent form of QuaDRiGa can be used for frequencies ranging from 0.45 to 100 GHz. One major improvement in the QuaDRiGa is its ability to generate correlated large-scale parameters (LSPs). The correlated maps in QuaDRiGa were created using a 2D map covering all receiver locations.

C. mmMAGIC Channel Model: The mmWave-based Mobile Radio Access network channel model for fifth Generation Integrated Communications (mmMAGIC) was developed using the 3GPP channel modeling approach and the QuaDRiGa as a foundation. In the mmMAGIC, the measurement data for modeling in frequency bands ranging from 6 GHz to 100 GHz can be obtained through measurement campaigns in environments such as airports, indoor offices, outdoor-to-indoor, UMi open square, and indoor offices.

D. METIS Channel Model: Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS) uses a map-based model, a stochastic model, and their combination, that is, a hybrid model, to achieve flexible and scalable channel modeling. The stochastic model and the map-based approach support frequency ranges of up to 100 GHz and 70 GHz, respectively. The map-based model was created using an RT methodology, a simplified 3D geometric description of a propagation environment, and additional random shadowing objects. Specular reflection, diffraction, diffuse scattering, and blocking were all considered propagation mechanisms. Specular and diffuse components can be enabled or disabled to improve accuracy or reduce complexity.

E. The 5GCMSIG: The special interest group (SIG), which is made up of several academic and industrial institutes, proposed the 5G Channel Model Special Interest Group (5GCMSIG) channel model. It has a large bandwidth and a wide frequency range (0.5–100 GHz) (100 MHz for below 6 GHz and 2 GHz for above 6 GHz). The 5GCMSIG extended the 3GPP 3D model to support higher frequency bands on the basis of extensive measurements and ray tracing simulations. This channel model consists of known models, such as shadowing, path loss, LOS probability, preliminary fast fading, and blockage models.

F. The 3GPP Channel Model: The most recent 3GPP channel model (3GPP TR38.901) is an expansion of the 3GPP 3D channel model and incorporates a number of additional modeling components. It has a large bandwidth and a wide frequency range (0.5–100 GHz), providing up to 10 percent of the carrier frequency. The 3GPP channel model was used to model the oxygen absorption at 53–67 GHz as a function of center frequency, delay, and 3D separation between the transmitter and the receiver.

G. IMT-2020 Channel Model: In order to add many new features, such as support for a broad frequency range up to 100 GHz, large bandwidth, 3D propagation modeling, spatial consistency, large antenna array, blockage modeling, and other emerging features, the IMT-2020 channel model was developed. It is a GBSM that builds on the IMT-Advanced channel model and the 3GPP TR36.873 channel model. The vegetation effects, which are based on the fact that mmWave signals can be attenuated and diffusely scattered by leaves and diffracted around the canopy of trees, in addition to gaseous absorption, were taken into consideration in this model.

H. IEEE 802.11ay Channel Model: The IEEE 802.11ad channel model, which was created for the 60 GHz range, is extended in IEEE 802.11ay (57–68 GHz). The IEEE 802.11ay model's multipath comprises D-rays, R-rays, and F-rays. It uses the Q-D channel modeling methodology inherited and extended from the MiWEBA model. The LOS ray, ground-reflected ray, and other rays reflected from scenario-relevant objects are all examples of the relatively powerful D-rays.

I. MG5GCM: Recently, a More General 5G Channel Model (MGCM) 3D non-stationary 5G channel model was proposed [172]. The model can cater to important 5G communication scenarios, such as massive MIMO, HST, V2V, and mmWave communication. The proposed model was created on the basis of the WINNER II and SV models. The array–time cluster evolution, i.e., the appearance and disappearance of clusters on the time and array axes, was modeled as a birth–death process. The delays, powers, and angles for newly generated clusters were generated at random on the basis of certain distributions at every time instant. Parameters for the survived clusters were updated on the basis of their geometrical relationships. To support massive MIMO communications, the spherical wavefront was calculated on the basis of the physical location of clusters.

J. NYUSIM Channel Model: The model was developed using millimeter wave (mmWave) field measurements. The NYUSIM was created using measurements from multiple mmWave frequencies ranging from 28 GHz to 73 GHz. The model is applicable for frequency ranges ranging from 0.5 to 100 GHz and RF bandwidths ranging from 0 to 800 MHz:

$$PL^{NYU}(f,d) = FSPL(f,1\text{ m}) + 10nlog_{10}(d) + AT + X_{\sigma}^{CI} \quad (50)$$

Note that $AT[\text{dB}] = \alpha[\text{dB/m}] \times d[\text{m}]$ where α is the frequency and AT is the atmospheric attenuation. In Table 11, a comparison of the general 5G channel models, with respect to their respective features, is given.

Table 11. Comparison of the general 5G channel models.

Features	COST 2100	MIWEBA	QuaDRiGa	METIS		5GCMSIG	3GPP	mmMAGIC	IMT-2020	IEEE 802.11ay	MG5GCM	NYUSIM
Modeling approach	GBSM	Q-D-based model	GBSM	Stochastic	Map-based	GBSM, GGBSM	GBSM, Map-based Hybrid model	GBSM, GGBSM	GBSM, TSP Map-based Hybrid model	Q-D-based model	GBSM	GBMS
Frequency range (GHz)	<6	57–66	0.45–100	Up to 70	Up to 100	0.5–100	0.5–100	6–100	0.5–100	57–68	-	0.5–100
Bandwidth (GHz)	-	2.16	1	0.1 (<6), 1 @ 60	10% of the center frequency	0.1 (<6), 2 (>6)	10% of the center frequency	2	0.1(<6), 10% of the center frequency (>6)	2.64	-	
Support large array	-			✘	✓	Limited	✓	✓	✓	✘	✓	
Support spherical waves	✘	✓		✘	✓	✘	✘	✓	✘	✘	✓	
Support dual-mobility	✘	✓	✘	Limited	✓	✘	✘	✘	✘	✓	✓	
Support 3D (elevation)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Support mmWave	x	✓	✓	Partially	✓	✓	✓	✓	✓	✓	✓	✓
Dynamic modeling	✓	Limited	✓	X	✓	✓	✓	✓	✓	Limited	✓	✓
Spatial consistency	✓	✓	✓	Shadow fading only	✓	✓	✓	✓	✓	✘	✘	✓
High mobility	✓	x	✓	Limited	x	✓	Limited	✓	Limited	✘	✓	✓
Blockage modeling	✘	✓	✘	✘	✓	✓	✓	✓	✓	✓	✘	✓
Gaseous absorption	✘	✓	✘	✘	✓	✘	✓	✓	✓	✓	✘	✓

7.5. The 5G Channel Modelling

The radio channel is a core pillar of wireless communication; it provides the desired understanding of radio signal performance. Essentially, the accuracy of the propagation channel determines all expected performance of a wireless communication system. As a result, it is critical to conduct a wide range of studies on the accurate modeling of a communication channel. Stochastic channel models and deterministic models are the two types of channel models covered in this review. Various approaches to propagation channel modeling are discussed in this section, and a summary of all applicable channel models is provided.

7.5.1. Deterministic Channel Model

Deterministic models utilize electromagnetic (EM) wave propagation principles to determine signal strength in any communication scenario. The reflection and diffraction laws are used to estimate the received signal strength at a specific geographical location, which can be specified using a 3D map of the targeted propagation scenario or environment [173]. Even though the deterministic modeling approach predicts signal propagation with high accuracy, it lacks computational efficiency and involves quite complicated processes. The following are some well-known deterministic modeling approaches:

A. Ray Tracing Model: The ray tracing deterministic approach is based on Geometric Optics (GO), Geometric Theory of Diffraction (GTD), and Uniform Theory of Diffraction (UTD), most of which can be used to simplify and approximate high-frequency electromagnetic propagation. Diffraction paths can be determined using GTD and UTD, while GO is used to determine direct, reflected, and refracted paths [174].

B. Map-Based Model: The map-based channel model is a deterministic modeling approach developed by METIS following extensive radio propagation research [73]. The model uses ray tracing and simplified three-dimensional geometric approaches for the description of the environment and, as such, can capture significant propagation mechanisms, such as scattering, specular reflection, blocking, and diffraction. This modeling approach provides accurate and realistic spatial channel properties and can also be applied for evaluating beamforming and massive MIMO, as well as realistic path loss modeling in V2V and D2D scenarios. To begin, a map is drawn with random objects. Then, diffuse scattering point sources and Tx/Rx locations are defined. Paths are then calculated using path lengths and arrival/departure angles. Shadowing loss, LOS, reflection, diffraction, and scattering are all components of the CIR.

C. Point Cloud Model: A point cloud model is a prediction tool used to characterize the environment with greater precision, comparable to ray tracing. The point cloud model data can be obtained using common methods, such as laser scanning, which produces accurate results and fine object structures. However, point cloud data cannot be used directly in ray tracing tools because no surface representation is available. Cloud points are first filtered to form local surfaces, and neighboring points are found, followed by normal and plane depths. Next, propagation mechanisms such as LOS, specular, and diffuse paths are considered. MPC parameters, such as amplitudes, delays, and angles, are computed. Finally, PDP is calculated from combined paths with bandwidth constraints.

7.5.2. Semi-Deterministic Model

Quasi-Deterministic (Q-D) Model: The Q-D modeling approach for mmWave channels in non-stationary environments was proposed and adopted by MiWEBA and the IEEE 802.11ay on the basis of measurements and ray tracing simulations. It is composed of various types of rays with varying activity percentages, known as deterministic rays (D-rays), random rays (R-rays), and flashing rays (F-rays). In the Q-D modeling approach, the D-rays are modeled deterministically, while the R- and F-rays are modeled stochastically. It employs the IEEE 803.11ad model to simulate power delay profiles (PDPs) [123]. A hybrid approach, such as ray tracing, is far more accurate than pure statistical approaches and does not require a detailed scenario description. The modeled channel includes power, delay, arrival and departure angles, and a ray polarization matrix.

7.5.3. Stochastic Model

Stochastic (Statistical Model): Combining measurements and observations yields stochastic models. These models, which are based on substantial experimental data and statistical analysis, allow us to compute the received signal intensity in a particular propagation medium. A stochastic model takes into account all environmental impacts or effects on model development. Regardless, the model produces more accurate and effective predictions when utilized in contexts comparable to the one for which it was built. Consequently, the models are more accurate and suited for the region where the measurement campaign was carried out, and they will need to be modified for use in other places. Some stochastic models are discussed in more detail as follows.

A. Geometry-Based Stochastic Models (GBSM): GBSMs have been extensively employed for channel modeling in a variety of situations, which include performance, coverage, and rate analysis of 5G and beyond communication systems at both the FR1 and FR2 frequency bands [175–177]. The two types of GBSMs are those with a regular shape (RS) and those with an irregular shape (IS). It is assumed that scatterers in RS-GBSMs are stochastically dispersed in accordance with a particular geometry and a regular form. Effective scatterers are thought to be found in regular forms, such as ellipses, cylinders, one-ring, and two-rings. However, scatterers in IS-GBSMs are assumed to be stochastically distributed rather than situated in a regular shape. It manifests as effective scatterer locations with various shapes [123]. IS GBSMs include the WINNER II and 3GPP spatial channel models (SCM). The channel modeling process starts with the network layout definition and determination of antenna parameters. Following that, the LOS/NLOS condition is assigned using the LOS probability model, and the PL is calculated using the PL model's small-scale parameters, such as delays cluster powers, and arrival and departure angles are then generated and randomly coupled. Finally, random initial phases are assigned, followed by the computation of channel coefficients.

B. Non-Geometrical Stochastic Models (NGSM): In V2V channel modeling, non-geometrical stochastic models, such as the tapped delay line (TDL) and clustered delay line (CDL) models, can also be employed. The channel impulse response (CIR) in TDL models is represented by a linear finite impulse response (FIR) filter. Each TDL model tap is made up of several MPCs with non-resolvable delays [178]. Using a correlation matrix, the TDL model provides a statistical description of the correlation between different antennas. In the 3GPPP report [179], three TDL models, known as as TDL-A, TDL-B, and TDL-C, were defined for representing three distinct channel profiles for the NLOS scenario, while TDL-D and TDL-E are for the LOS scenario. On the other hand, the CDL models are used for modeling signal direction in phase. It performs modeling on the basis of the description of directions of arrival and departure of the signal in space and the corresponding number of clusters to the number of channel reflections [178]. Just like for TDL, 3GPP defined three CDL models, namely CDL-A, CDL-B, and CDL-C, for representing NLOS channel profiles, while CDL-D and CDL-E are for LOS channels. Another type of NGSM is the Correlation-Based Stochastic Model (CBSM), which tends to model the correlation between antenna elements to describe the spatial structure of a wireless channel (such as MIMO).

C. Saleh–Valenzuela (SV) Model: The SV-based model is commonly employed to simulate Channel Impulse Response (CIR) in indoor scenarios. In the SV model, it is assumed that rays reach clusters in the delay domain. The delay distribution follows a Poisson distribution, while the inter-arrival times are distributed exponentially. Cluster power decay rate, ray power decay rate, cluster arrival rate, and ray arrival rate are some of the parameters used to describe CIRs. The SV model is modified in the IEEE 802.11ad channel model to include both pre-cursor and post-cursor decay rates in each cluster.

D. Propagation Graph Model: Forecasting the exponentially decaying PDP with specular to diffuse components is possible using the propagation graph channel model. As a result, it is suitable for simulating mmWave channels. The propagation graph model operates on the basis of the graph theory, and a graph is made up of two unconnected sets of edges and vertices. In this model, vertices represent transmitters, receivers, and scatterers, and probability-valued edges represent propagation conditions between the vertices. Angle information can be obtained from the geometry distributions of transmitters, receivers, and scatterers. Figure 16 gives a taxonomy of 5G channel models. Table 12 presents a summary of approaches to channel modeling [174].

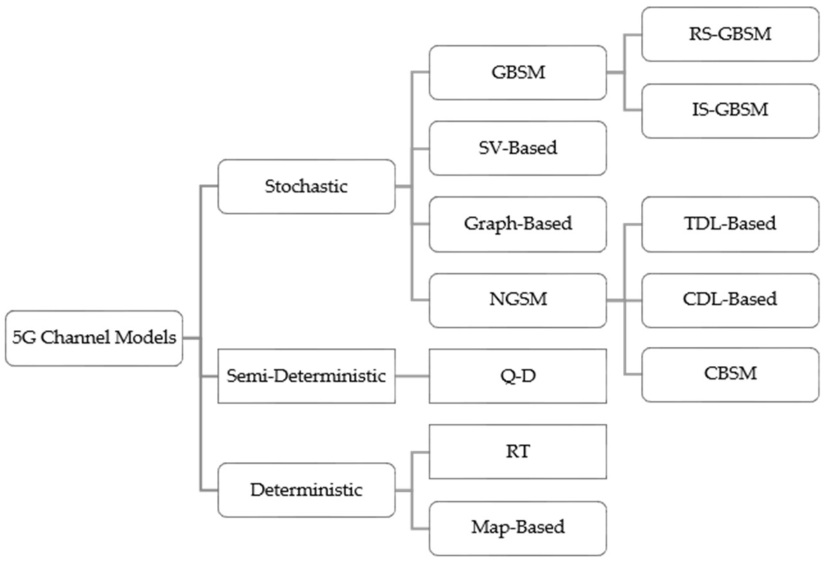

Figure 16. Taxonomy of 5G Channel Models.

Table 12. Summary of approaches to channel modeling.

Model	Deterministic/Stochastic	Example	Environment	Features
Ray Tracing	Deterministic	IEEE 802.11AD	Indoor/Outdoor	Site-specific and high complexity
Map-based	Deterministic	METIS	Indoor/Outdoor	Support massive MIMO and beamforming
Point Cloud	Deterministic	-	Indoor	Characterize the environment with precision
Q-D	Semi-deterministic	MiWWEBA and IEEE 802.11ay	Outdoor	Support non-stationary environments
SV	Stochastic	IEEE 802.15.3c and IEEE 802.11ad	Indoor	For CIR simulations
Propagation graph	Stochastic	-	Indoor	Predict PDP transition from specular to diffuse
GBSM	Stochastic	NYU WIRELESS, 3GPP TR 38.901, METIS, and mmMAGIC	Indoor/Outdoor	Characterize 3D and non-stationary properties
NGBSM	Stochastic	-	Indoor/Outdoor	-

8. Challenges, Future Directions, and Lessons Learned

The key challenges and future research directions are broached in this section.

8.1. Challenges

Despite the enormous advantages of the 5G network, several challenges must be overcome to have a seamless and effective network deployment. Radio frequency (RF) spectrum scarcity is one of the most critical challenges. The available frequency has been heavily used, making it difficult for operators to obtain new ones. A few of the several challenges are discussed as follows.

a. Interference Management: A common issue with 5G networks is handling interference among 5G devices, especially as the number of communicating devices increases [180,181]. This is because, as the number of communicating devices and user applications increases, the interference in the network will also increase. The 5G network interference may be a result of the UE receiving interference from multiple macro-cell base stations (MBSs), other UEs, or interferences from small-cell base stations (SBSs) [182]. It is, thus, essential to find an effective interference management approach for 5G processes, such as power control, channel allocation, and load balancing.
b. Environmentally Unfriendly: Wireless communication technologies consume lots of energy, leading to very high carbon emissions, which are very harmful to the environment. The current radio access network consumes approximately 70% to 80% of the total power [183]. It is, thus, very important to develop communication systems, technologies, and hardware that will be more energy-efficient and friendly to the environment.
c. Network and UE Security and Privacy: The several encouraging features of 5G networks pose difficult challenges in the design of secure 5G networks. A large number of new communication devices, for example, may be the source of various types of attacks, such as impersonation, denial-of-service (DoS), eavesdropping, repudiation attacks, and other cyber-attacks. Another issue occurs when a large volume of data needs to be transmitted quickly and securely.
d. Economic Challenges: In terms of deployment and user incentive, a paradigm change in future mobile communications technology would have substantial economic repercussions. Because of the extraordinarily high demand for communication services in urban and rural regions, communication equipment costs are growing rapidly. Another element contributing to the high cost is the requirement for mobile operators to construct a whole new infrastructure to fulfill the tremendous demand. As a result, from the standpoint of government, regulatory bodies, and network operators, the cost of infrastructure development, maintenance, administration, and operation should be affordable. Furthermore, the cost of utilizing D2D communication should be affordable, with D2D communication devices charging no more than the cost of using a BS's services. Furthermore, revenue growth is expected to be significantly lower than traffic growth; hence, 5G networks must be built to benefit all stakeholders, including the government, network operators, and customers.
e. Health and Safety: This is another critical challenge of the 5G network because the network utilizes the millimeter wave (mmWave) in addition to the microwave utilized in the previous generations and as discussed earlier. Although the millimeter wave has a very large bandwidth, it cannot travel over a long distance because various atmospheric parameters easily attenuate it. This, then, presents the need to install the 5G antennas very close to one another and to the users in small cells, which, thus, results in the constant exposure of the users to the millimeter wave radiation [184]. This had raised concerns even before the deployment of the network, where different analyses and experiments were conducted to evaluate the radiation level and its effect on human health [185].

f. Commercialization challenge: various factors can hinder the commercialization or deployment of the 5G network, which include inadequate optical fiber penetration, lack of civil infrastructure, lack of electrical power supply, cost of spectrum and equipment, etc., in some regions or countries, particular in Nigeria where the 5G network is yet to fully deployed [186]. This poses a great challenge to the 5G network for both the users and the telecommunication operators, as the need to provide these amenities in the regions or countries can further increase the cost of deployment, which can lead to an increase on the part of the users of the network. Thus, there is a need to design the network such that the cost of using the network would be minimal.

8.2. Future Directions

This paper provides an in-depth look at the 5G mobile network and the technologies that enable its adoption. These technologies make 5G more trustworthy, scalable, and cost-effective. As previously described, several technological obstacles occur when deploying such technologies or offering services via a 5G mobile network. Undoubtedly, several studies have been carried out on 5G communication, especially as it relates to enabling technologies, frequency standardization, and propagation models [17,70,156,187–189]. However, there are still open research directions that are yet to be thoroughly explored. In this section, we identified some key areas where further research is needed. We have also considered proposals from several researchers on the integration of new technologies to facilitate the development and quick implementation of the 5G technology.

a. Blockchain technology for improved security: Since the development of 5G and beyond 5G networks must accommodate millions of networked devices, security and privacy are crucial considerations. Networks for 5G and beyond must address user data confidentiality and privacy concerns. To ensure the effective deployment of such networks, these difficulties must be addressed from the perspectives of service providers, network operators, and vendors in addition to those of consumers. Researchers are working on several ways to enhance security and privacy in 5G networks. Some of such recent attempts are works on the implementation of blockchain technology in 5G networks for better security and privacy [190,191]. To further improve security and privacy in 5G and future networks, the possibility of combining blockchain technology with other technologies, such as the NFV and SDN, will be a promising area for researchers to explore.
b. Energy efficiency: low-complexity and low-cost optimization models are essential to meet the next-generation wireless systems' critically demanding green standards, streamlined deployment, and effective energy-saving. Because of the higher density of wireless access points, wider bandwidths, and more antennas used in 5G and beyond-5G systems compared with past generations of wireless communication networks, there are now more environmental and financial problems. As a result, EE is now a crucial prerequisite for constructing a new wireless network. Highly detailed power models, effective energy management approaches, and more advanced optimization techniques are needed to overcome this challenge.
c. Green 5G communication: Mobile network operators and device manufacturers have repeatedly tried to create an energy-efficient network in response to the mounting concerns over harmful carbon emissions and their negative environmental impact. Numerous cutting-edge solutions have been proposed to lower conventional energy usage and establish a 5G communication network that is sustainable [192–195], as one of the primary goals of the 5G system is to develop an energy-efficient network. One of these topics that require more research by academics is the utilization of green energy. Two examples of green 5G enablers that show potential for boosting energy efficiency and lowering reliance on traditional energy sources while also promoting environmental safety are energy harvesting and smart grid integration [194].
d. Multi-connectivity: Finding a suitable solution to handle a large number of users who will be using the 5G network as a result of the ongoing rise in user demand

for high bandwidth is important. The prospect of combining multiple radio access technologies, such as satellite and cellular technologies, with various types of new technologies, such as femtocells and picocells, to create a 5G network communication system is an ideal topic to investigate. Multi-connectivity, which is based on heterogeneous architecture and enables the user equipment to employ component carriers from different base stations and Wi-Fi access points, is one of these unique approaches [196,197]. The performance aspect of interference, mobility, and spectrum management for 5G technology may be improved with more studies focused on this area.

e. Spectrum management mechanism: Modern wireless applications have significantly raised the demand for spectrum resources. To overcome the issue of spectrum scarcity, achieve high data rates, and ensure good quality of service, spectrum sharing is seen as a crucial method for 5G networks (QoS). Even though various studies have been conducted on coming up with a suitable plan for 5G spectrum management [198,199], more work needs to be done to obtain cutting-edge technology that will satisfy future spectrum demands.

f. Introduction of Reconfigurable Intelligent Surfaces (RIS): An RIS is a specifically designed human-made surface of electromagnetic (EM) material that is electronically controlled with integrated electronics and has unnatural wireless communication capabilities. In the most commonly considered case, the large number of small-sized, low-cost, and almost passive elements that comprise a RIS can simply modify the incident signal over the air to improve the signal coverage and quality [200,201]. RISs offers a potential solution to achieve a software-configurable smart radio environment. The most distinguishable property of RISs is their inexpensive, nearly passive panel of unit cells. Even though some works [200–202] have been conducted in this area, further research efforts are still necessary, especially on its application to solving the 5G millimeter wave propagation challenges, such as blockage and absorption experienced at higher frequencies.

g. Application of the emerging graph-based deep learning methods: Graph Neural Networks (GNNs) are forms of artificial intelligence techniques that use the graph-based deep learning method to predict the nodes, edges, and graph-related tasks after training the graph-based data sets. They are used for graph and node classification, link predictions, graph clustering, and generating, as well as image and text classification [203]. Traditional challenges in 5G systems, such as routing, load balancing, power control and resource allocation, and emerging ones, such as virtual network embedding in Software Defined Networking, can be solved when deep learning models, such as the GNN, are applied. Researchers use GNN to mine deep information hidden in graph-structured data to further improve the abilities to learn and simulate interactions between network nodes [204]. These Deep Learning techniques are being applied to wireless communications to combat problems such as resource allocations, physical layer design, and networking [205]. Further research efforts on applying the GNN deep learning approach to 5G technology will undoubtedly pose solutions to routing, power control, and QoS issues.

h. Introduction of Semantic Communication (SemCom): The introduction of very advanced artificially intelligent approaches needs to be investigated to achieve the high transmission rate needed for 5G communication systems that go beyond the requirements of the traditional enabling technologies. Semantic communication integration is one of these strategies, as it integrates all aspects of the network, including users, their specific service needs, and the meaning of the information being transmitted into data processing and transmission [206,207], by leveraging AI technology to communicate the most pertinent information to the receiver. Unlike traditional data-oriented transmission, SemCom recognizes and uses the meaning of information during the process of communication over the Internet, thereby reducing network load. Because SemCom strives to convey the meaning of the data and not only replicate the actual transmitted data, other undesirable phenomena, such as obstruction and air absorption observed at higher frequencies, will also be avoided [208,209]. The 5G system will successfully communicate the meaning of transmitted information while utilizing a significantly reduced amount of bandwidth, thanks to SemCom [207]. Integration of this novel technology into the 5G network is, thus, an area that requires more research effort [210].

8.3. Lessons Learned

In this section, a summary of lessons learned from this survey is presented.

1. Just as noted above, the demand for greater mobility and coverage, communications with microsecond latency, and ultra-high data speeds have soared exponentially. To keep up with the rapid advancement of ground-breaking applications, wireless service requirements, and sophisticated social needs, wireless networks are currently being updated beyond 4G systems. Even if current technologies, such as the 4G architecture, are made to offer ubiquitous wireless access and significantly reduce latency, they also have to contend with growing technological demands for better QoS, more system capacity, and faster data rates. The deployment of flexible frequency plans, small cell technology, energy-efficient transmission techniques, and other disruptive technologies in conjunction with cutting-edge security and blockchain approaches are envisaged to address these requirements in 5G and beyond technologies.
2. With the introduction of 5G technology, greater frequency allocation and adaptable spectrum management methodologies will surely be necessary to offer seamless mobile broadband support for current and future data-hungry applications. This new frequency standardization should be compatible with the more contemporary technology and services that enable 5G and other wireless communication standards. Because 5G has been designed to operate on many spectrum bands, including the licensed, unlicensed, and shared bands of the FR1 and FR 2 bands, the combination of both frequency divisions will ensure a perfect balance between providing short-range and long-range communication. Thus, it is imperative that to satisfy a range of requirements, such as those for high data rates, high reliability, the Internet of Things, and low-latency communication, these frequencies must be carefully chosen.
3. The adoption of Device-to-Device communication approaches in the current 5G network and beyond will provide better spectrum efficiency, power management, coverage, and capacity expansion, especially when radio resource reuse is implemented. Additionally, to avoid the problem of intra-cell interference, solutions such as network coding and interference avoidance multi-antenna transmission can be employed.
4. Network virtualization can reduce the load on the 5G network, allowing for more flexible service operation and simpler deployment across several sites. The NFV interface contains several virtual tools, such as machines, hypervisors, and network operations, requiring high security. To guarantee data security and the detection of malicious software in virtual functions, trusted computing can be used to make sure that only trusted software is operating on the NFV interface.
5. Blockchain technology can be used to deploy 5G and future networks. It offers many security advantages, such as full control over information when transmitted over an unsecured, unprotected network, better system performance because it does not need a centralized system to work, and network simplification.
6. Multiple antennas can be used at the transmitter and receiver ends as a successful strategy to increase spectral efficiency while lowering hardware complexity. However, addressing inter-cell interference causes the implementation to be more challenging due to the energy-intensive nature of signal processing at the BS. One of the best techniques for simplifying the MIMO network is spatial modulation (SM), which sees the antenna arrays as a spatial constellation diagram, with each antenna carrying a series of data bits.
7. When many base stations are employed, green communication can be introduced to reduce energy consumption by the base stations and, hence, lessen environmental hazards. Energy efficiency can be increased by utilizing less RF transmit power.

Another tactic for achieving energy efficiency is utilizing a duty cycle device, which disables some base stations with low traffic.

9. Conclusions

This paper reviewed the enabling technologies underpinning the seamless deployment of 5G networks. The article systematically evaluated more than twenty 5G major enabling technologies identified in previous review studies which were conducted between 2010 and 2022. The evolution of mobile networks tracing from 1G to 6G, different 5G use cases, and significant future research objectives are all presented. Findings from this review work revealed that, while there are numerous enabling technologies for 5G, the mmWave and massive MIMO technologies are the most prominent that have undergone in-depth and critical study by researchers. This study similarly found that the global 5G deployment trials are predominantly in Asia, America, and Europe; only a few trials were found in African nations. Furthermore, the favored Non-Standalone approach for the early commercial roll-out of the 5G networks has focused on the 5G FR1 bands, whereas the FR2 bands have been given little attention despite their superior bandwidth. It is worth noting that the QoS requirements of applications must be carefully defined in order to choose the best band for deployment. This work identified a number of important explorable research directions to improve the 5G communication networks further, particularly as they will aid the transition to the envisioned 6G technology. Certainly, this review will allow 5G researchers to quickly gain a general understanding of the various 5G technologies and other key topics without wading through a large pool of existing literature. Last, this survey reveals the benefits of these diverse technologies in developing a robust, flexible, dependable, and scalable 5G network. Future work would review system modeling and propagation measurements in 5G and beyond 5G wireless communication systems.

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Abbreviations

3GPP	Third Generation Partnership Project
5G PPP	5G Infrastructure Public–Private Partnership
5GNOW	5th Generation Non-Orthogonal Waveforms for Asynchronous Signaling
5GIC	5G Innovation Centre

5GCMSIG	5G Channel Model
AMPS	Advanced Mobile Phone System
AR	Augmented Reality
ARIB	Association of Radio Industries and Businesses
AI	Artificial Intelligence
ATIS	Alliance for Telecommunications Industry Solutions
ASA	Authorized Spectrum Access
ASA	Azimuth Angle Spread of Arrival
ASD	Azimuth Angle Spread of Departure
BDMA	Beam Division Multiple Access
BER	Bit Error Rate
BS	Base Station
CA	Carrier Aggregation
CBSM	Correlation-Based Stochastic Models
CCs	Carrier Components
CCSA	China Communications Standards Association
CDMA	Code Division Multiple Access
CDL	Clustered Delay Line
CI	Close-In
CIR	Channel Impulse Response
CPU	Central Processing Unit
CQI	Channel Quality Index
CSI	Channel State Information
D2D	Device-to-Device
D-rays	Deterministic rays
DL	Downlink
DSS	Dynamic Spectrum Sharing
DC	Dual Connectivity
DoF	Degree of Freedom
ETRI	Electronics and Telecommunication Research Institute
EDGE	Enhanced Data Rates for GSM Evolution
EE	Energy Efficiency
EM	Electromagnetic
eMTC	Enhanced Machine-Type Communication
eMBB	Enhanced Mobile Broadband
ETSI	European Telecommunication Standards Institute
EMPHATIC	Enhanced Multicarrier Technology for Professional Ad Hoc and Cell-Based Communications
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
EVDO	Evolution Data Optimized
FBMC	Filter Bank Multi-Carrier under Frequency Selective Channels
FDMA	Frequency Division Multiple Access
FEC	Forward Error Corrections
FDD	Frequency Division Duplex
FIR	Finite Impulse Response Filter
FR1	Frequency Range 1
FR2	Frequency Range 2
F-rays	Flashing Rays
GAA	General Authorized Access
GBSM	Geometry-Based Stochastic Models
GSA	Global Mobile Suppliers Association
GSM	Global System for Mobile Communication
GPRS	General Packet Radio Services
GO	Geometric Optics
GTD	Geometric Theory of Diffraction
H2H	Human-to-Human Communications
HSDPA	High-Speed Downlink Packet Access
HSPA	High-Speed Packet Access
HSUPA	High-Speed Uplink Packet Access
IAB	Integrated Access Backhaul

IS	Irregular Shape
ISGBSMs	Irregular Shape Geometry-Based Stochastic Models
IMS	IP Multimedia Subsystems
IoT	Internet of Things
ITU	International Telecommunications Union
ITU-R	International Telecommunications Union Radiocommunication Sector
KPI	Key Performance Indicator
LoS	Line-of-Sight
LSA	Licensed Shared Access
LTE	Long-Term Evolution
LTE-A	Long-Term Evolution Advanced
LTE EPC	Long-Term Evolution Evolved Packet Core
LTE-LAA	Long-Term Evolution Licensed Assisted Access
LTE-M	Long-Term Evolution Machine
LTE-U	Long-Term Evolution Unlicensed
MAC	Media Access Control
MEC	Multi-access Edge Computing
METIS	Mobile and wireless communications Enablers for Twenty-twenty (2020) Information Society
M-LWDF	Maximum-Largest Weighted Delay First
mMTC	Massive Machine-type Communications
MBMS	Multimedia Broadcast/Multimedia Service
MGCM	Meridian General Packet Module
MIMO	Multiple Input Multiple Output
M-MIMO	Massive MIMO
MU-MIMO	Multi-User MIMO
MMS	Multimedia Messaging Service
mmWave	Millimeter Wave
MTC	Maintenance Timing and Control Technology
M2M	Machine-to-Machine
NEWCOM	Network of Excellence in Wireless Communications
NR	New Radio
NB-IoT	Narrow Band IoT
NFC	Near Field Communication
NFV	Network Function Virtualization
NGSMs	Non-Geometrical Stochastic Models
NOMA	Non-Orthogonal Multiple Access
NSA	Non-Standalone
NYU Wireless	New York University Wireless
NYUSIM	New York University Simulator
NLOS	Non-Line-of-Sight
OSI	Open System Interconnection
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
OMA	Orthogonal Multiple Access
PAL	Priority Access Licensed users
PDP	Power Delay Profiles
PoC	Push-to-Talk over Cellular
PL	Path Length
PLE	Public Local Exchange
PWS	Public Warning System
PSTN	Public Switched Telephone Network
QAM	Quadrature Amplitude Modulation
Q-D	Quasi-Deterministic
QoS	Quality of Service
QoE	Quality of Experience
RF	Radio Frequency
RMS	Record Management System
R-rays	Random Rays
RAN	Radio Access Network

RBs	Resource Blocks
RAT	Radio Access Technology
RS	Regular Shape
RS-GBSMs	Regular Shape Geometry-Based Stochastic Models
RT	Real Time
Rx	Receiver
SA	Standalone
SV	Saleh–Valenzuela
SAE	System Architecture Evolution
SCM	Sub Carrier Multiplexing
SC-NOMA	Single Carrier Non-Orthogonal Multiple Access
SC-FDMA	Single Carrier Frequency Division Multiple Access
SMS	Short Message Services
SNR	Signal-to-Noise Ratio
SU-MIMO	Single User MIMO
SUDAS	Shared User Equipment-Side Distributed Antenna System
SAS	Spectrum Access System
SF	Shadowing Factor
SFC	Service Function Chaining
SLAs	Service Level Agreements
STFT	Short-Term Fourier Transform
TCP	Transmission Control Protocol
TDD	Test-Driven Development
TDL	Tapped Delay Line
TDMA	Time Division Multiple Access
TVWS	Television White Spaces
TTA	Telecommunications Technology Association
TTC	Telecommunications Technology Committee
TSDSI	Telecommunications Standards Development Society of India
Tx	Transmitter
UCs	Use Cases
UDN	Ultra-Dense Networks
UE	User Equipment
UHD	Ultra-High Definition
UL	Uplink
UMTS	Universal Mobile Telecommunication System
URLLC	Ultra-Reliable Low-Latency Communication
UTD	Uniform Theory of Diffraction
VNFs	Virtual Network Functions
VR	Virtual Reality
V2X	Vehicle-to-Everything
V2P	Vehicle-to-Pedestrian
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
ZSA	Zenith Angle Spread of Arrival
ZSD	Zenith Angle Spread of Departure

List of Symbols

$\mathbf{H}$	Channel vector
$\mathbf{X}$	User signal
α	Floating intercept
β	Slope
γ	Path length and frequency component of the path loss of the link
h_k	Channel vector between k_{th} user and base station
σ^{FI}	Standard deviation
b	Optimization parameter
n	Path loss exponent
f_c	Center frequency

f	Carrier frequency
f_o	Operating frequency
f_w	Weighted frequency
N_k	Total number of recorded data
f_k	Corresponding frequency
L	Free space loss at a distance of 1 m
AT	Atmospheric attenuation
$n_{download}$	Additional noise
n_{noise}	Receiver noise
X_σ^{CI}	Gaussian random variable
D	Transmitter-to-receiver separation

References

1. Meng, X.; Li, J.; Zhou, D.; Yang, D. 5G Technology Requirements and Related Test Environments for Evaluation. *China Commun.* **2016**, *13*, 42–51. [CrossRef]
2. Navarro-Ortiz, J.; Romero-Diaz, P.; Sendra, S.; Ameigeiras, P.; Ramos-Munoz, J.J.; Lopez-Soler, J.M. A Survey on 5G Usage Scenarios and Traffic Models. *IEEE Commun. Surv. Tutor.* **2020**, *22*, 905–929. [CrossRef]
3. Yuan, J.; Shan, H.; Huang, A.; Quek, T.Q.S.; Yao, Y.-D. Massive Machine-to-Machine Communications in Cellular Network: Distributed Queueing Random Access Meets MIMO. *IEEE Access* **2017**, *5*, 2981–2993. [CrossRef]
4. Le, N.T.; Hossain, M.A.; Islam, A.; Kim, D.; Choi, Y.-J.; Jang, Y.M. Survey of Promising Technologies for 5G Networks. *Mob. Inf. Syst.* **2016**, *2016*, 1–25. [CrossRef]
5. Liu, G.; Huang, Y.; Chen, Z.; Liu, L.; Wang, Q.; Li, N. 5G Deployment: Standalone vs. Non-Standalone from the Operator Perspective. *IEEE Commun. Mag.* **2020**, *58*, 83–89. [CrossRef]
6. Adedoyin, M.A.; Falowo, O.E. Combination of Ultra-Dense Networks and Other 5G Enabling Technologies: A Survey. *IEEE Access* **2020**, *8*, 22893–22932. [CrossRef]
7. Adoga, H.U.; Pezaros, D.P. Network Function Virtualization and Service Function Chaining Frameworks: A Comprehensive Review of Requirements, Objectives, Implementations, and Open Research Challenges. *Future Internet* **2022**, *14*, 59. [CrossRef]
8. Ahad, A.; Tahir, M.; Aman Sheikh, M.; Ahmed, K.I.; Mughees, A.; Numani, A. Technologies Trend towards 5G Network for Smart Health-Care Using IoT: A Review. *Sensors* **2020**, *20*, 4047. [CrossRef] [PubMed]
9. Dangi, R.; Lalwani, P.; Choudhary, G.; You, I.; Pau, G. Study and Investigation on 5G Technology: A Systematic Review. *Sensors* **2021**, *22*, 26. [CrossRef]
10. Hossain, E.; Hasan, M. 5G Cellular: Key Enabling Technologies and Research Challenges. *IEEE Instrum. Meas. Mag.* **2015**, *18*, 11–21. [CrossRef]
11. Islam, N.; Wahab, A.W.A. 5G Networks: A Holistic View of Enabling Technologies and Research Challenges. *Enabling Technol. Archit. Next-Gener. Netw. Capab.* **2019**, 37–70. [CrossRef]
12. Lee, J.; Tejedor, E.; Ranta-aho, K.; Wang, H.; Lee, K.-T.; Semaan, E.; Mohyeldin, E.; Song, J.; Bergljung, C.; Jung, S. Spectrum for 5G: Global Status, Challenges, and Enabling Technologies. *IEEE Commun. Mag.* **2018**, *56*, 12–18. [CrossRef]
13. Ramesh, M.; Priya, C.G.; Ananthakirupa, V.P.M.B.A.A. Design of Efficient Massive MIMO for 5G Systems-Present and Past: A Review. In Proceedings of the 2017 International Conference on Intelligent Computing and Control, I2C2 2017, Coimbatore, India, 23–24 June 2017.
14. Shafique, K.; Khawaja, B.A.; Sabir, F.; Qazi, S.; Mustaqim, M. Internet of Things (IoT) for Next-Generation Smart Systems: A Review of Current Challenges, Future Trends and Prospects for Emerging 5G-IoT Scenarios. *IEEE Access* **2020**, *8*, 23022–23040. [CrossRef]
15. Sharma, S.; Deivakani, M.; Reddy, K.S.; Gnanasekar, A.K.; Aparna, G. Key Enabling Technologies of 5G Wireless Mobile Communication. *J. Phys. Conf. Ser.* **2021**, *1817*, 12003. [CrossRef]
16. Zafarullah Noohani, M.; Ullah Magsi, K. A Review of 5G Technology: Architecture, Security and Wide Applications. *Int. Res. J. Eng. Technol.* **2020**, *7*, 3440–3471.
17. Swami, K.; Shukla, M.; Sharma, P. 5G and Its Enabled Technologies. *J. Anal. Comput. (JAC)* **2021**, *XV*. Available online: https://www.ijaconline.com/wp-content/uploads/2021/06/16.pdf (accessed on 22 November 2022).
18. Idowu-Bismark, O.; Okokpujie, K.; Husbands, R.; Adedokun, M. 5G Wireless Communication Network Architecture and Its Key Enabling Technologies. *Int. Rev. Aerosp. Eng. (IREASE)* **2019**, *12*, 70. [CrossRef]
19. Saeid, E.; Osman, W. 5th Generation Cellular Communication Systems Enabling Technologies and Challenges. *Int. J. Innovative Tech. Appl. Sci.* **2017**, *1*, 19–25.
20. Kaur, P.; Garg, R. A Survey on Key Enabling Technologies towards 5G. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1033*, 12011. [CrossRef]
21. Yu, Y.; Zhu, L. Application Scenarios and Enabling Technologies of 5G. *China Commun.* **2014**, *11*, 69–79. [CrossRef]
22. Talwar, S.; Choudhury, D.; Dimou, K.; Aryafar, E.; Bangerter, B.; Stewart, K. Enabling Technologies and Architectures for 5G Wireless. In Proceedings of the 2014 IEEE MTT-S International Microwave Symposium (IMS2014) 2014, Tampa, FL, USA, 1–6 June 2014.

23. Saha, R.K.; Saengudomlert, P.; Aswakul, C. Evolution Toward 5G Mobile Networks—A Survey on Enabling Technologies. *Eng. J.* **2016**, *20*, 87–119. [CrossRef]
24. Cardona, N.; Correia, L.M.; Calabuig, D. Key Enabling Technologies for 5G: Millimeter-Wave and Massive MIMO. *Int. J. Wirel Inf. Netw.* **2017**, *24*, 201–203. [CrossRef]
25. El Hassani, S.; Haidinel, A.; Jebbar, H. Road to 5G: Key Enabling Technologies. *J. Commun.* **2019**, 1034–1048. [CrossRef]
26. Al-Falahy, N.; Alani, O.Y. Technologies for 5G Networks: Challenges and Opportunities. *IT Prof.* **2017**, *19*, 12–20. [CrossRef]
27. Bega, D.; Gramaglia, M.; Bernardos Cano, C.J.; Banchs, A.; Costa-Perez, X. Toward the Network of the Future: From Enabling Technologies to 5G Concepts. *Trans. Emerg. Telecommun. Technol.* **2017**, *28*, e3205. [CrossRef]
28. Alimi, I.A.; Patel, R.K.; Muga, N.J.; Pinto, A.N.; Teixeira, A.L.; Monteiro, P.P. Towards Enhanced Mobile Broadband Communications: A Tutorial on Enabling Technologies, Design Considerations, and Prospects of 5G and beyond Fixed Wireless Access Networks. *Appl. Sci.* **2021**, *11*, 10427. [CrossRef]
29. Farooq, M.U.; Waseem, M.; Qadri, M.T.; Waqar, M. Understanding 5G Wireless Cellular Network: Challenges, Emerging Research Directions and Enabling Technologies. *Wirel. Pers. Commun.* **2016**, *95*, 261–285. [CrossRef]
30. Kumar, V.; Yadav, S.; Sandeep, D.N.; Dhok, S.B.; Barik, R.K.; Dubey, H. 5G Cellular: Concept, Research Work and Enabling Technologies. *Lect. Notes Netw. Syst.* **2019**, *39*, 327–338.
31. Liang, Q.; Durrani, T.S.; Liang, J.; Wang, X. Enabling Technologies for 5G Mobile Systems. *Mob. Inf. Syst.* **2016**, *2016*, 1–2. [CrossRef]
32. 5G Enabling Technologies: Network Virtualization and Wireless Energy Harvesting. *5G Phys. Layer Technol.* **2019**, 99–149.
33. 5G Enabling Technologies: Small Cells, Full-Duplex Communications, and Full-Dimension MIMO Technologies. *5G Phys. Layer Technol.* **2019**, 43–98.
34. Nguyen, V.G.; Brunstrom, A.; Grinnemo, K.J.; Taheri, J. 5G Mobile Networks: Requirements, Enabling Technologies, and Research Activities. *A Compr. Guide 5G Secur.* **2018**, 31–57.
35. Akyildiz, I.F.; Nie, S.; Lin, S.-C.; Chandrasekaran, M. 5G Roadmap: 10 Key Enabling Technologies. *Comput. Netw.* **2016**, *106*, 17–48. [CrossRef]
36. Agarwal, A.; Misra, G.; Agarwal, S.; Ghosh, K. 5G Wireless Cellular Networks: A Conceptual Analysis on Perception, Network Requirements and Enabling Technologies. *J. Inst. Eng. (India) Ser. B* **2018**, *100*, 187–191. [CrossRef]
37. Yuan, Y.; Zhao, X. 5G: Vision, Scenarios and Enabling Technologies. *Zte Commun.* **2015**, *13*, 3–10.
38. Kim, H.; Lee, S. *A Survey on the Key Enabling Technologies for the 5G Mobile Broadband Networks*; 2016; pp. 27–36. Available online: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=24f1f3e9ce3c92614e0a22065d4778ecf4545260 (accessed on 7 November 2022).
39. Amali, C.; Ramachandran, B. Enabling Key Technologies and Emerging Research Challenges Ahead of 5G Networks: An Extensive Survey. *JOIV Int. J. Inform. Vis.* **2018**, *2*, 133. [CrossRef]
40. Maitra, A. Early History of Wireless Communications. Souvenir of 33rd Annual Convention of Radio Physics and Electronics Association, University of Calcutta. 2003. Available online: https://www.researchgate.net/publication/283153440_EARLY_HISTORY_OF_WIRELESS_COMMUNICATIONS (accessed on 1 December 2022).
41. Mahmud, H. Cellular Mobile Technologies (1G to 5G) and Massive MIMO. *Int. J. Sci. Res. (IJSR)* **2019**, *8*, 929–937.
42. Anju, M.; Gawas, U. An Overview on Evolution of Mobile Wireless Communication Networks: 1G-6G. *Int. J. Recent Innov. Trends Comput. Commun.* **2015**, *3*, 3130–3133.
43. Patel, S.; Shah, V.; Kansara, M. Comparative Study of 2G, 3G and 4G. *Int. J. Sci. Res. Comput. Sci. Eng. Inf. Technol.* **2018**, *3*, 1962–1964.
44. Bandi, A. A Review Towards AI Empowered 6G Communication Requirements, Applications, and Technologies in Mobile Edge Computing. In Proceedings of the 6th International Conference on Computing Methodologies and Communication, ICCMC 2022, Erode, India, 29–31 March 2022; pp. 12–17.
45. Ajani, T.S.; Imoize, A.L.; Atayero, A.A. An overview of machine learning within embedded and mobile devices—Optimizations and applications. *Sensors* **2021**, *21*, 4412. [CrossRef]
46. Ismail, L.; Buyya, R. Artificial Intelligence Applications and Self-Learning 6G Networks for Smart Cities Digital Ecosystems: Taxonomy, Challenges, and Future Directions. *Sensors* **2022**, *22*, 5750. [CrossRef] [PubMed]
47. Ghildiyal, Y.; Singh, R.; Alkhayyat, A.; Gehlot, A.; Malik, P.; Sharma, R.; Akram, S.V.; Alkwai, L.M. An Imperative Role of 6G Communication with Perspective of Industry 4.0: Challenges and Research Directions. *Sustain. Energy Technol. Assess.* **2023**, *56*. [CrossRef]
48. Imoize, A.L.; Adedeji, O.; Tandiya, N.; Shetty, S. 6G Enabled Smart Infrastructure for Sustainable Society: Opportunities, Challenges, and Research Roadmap. *Sensors* **2021**, *21*, 1709. [CrossRef]
49. Alraih, S.; Shayea, I.; Behjati, M.; Nordin, R.; Abdullah, N.F.; Abu-Samah, A.; Nandi, D. Revolution or Evolution? Technical Requirements and Considerations towards 6G Mobile Communications. *Sensors* **2022**, *22*, 762. [CrossRef] [PubMed]
50. Prasad, R.K.; Sale, D.; Dhanvijay, M.M. Survey of MobileCommunication Systems. *Int. J. Res. Anal. Rev.* **2019**, *6*, 117–122.
51. Bertenyi, B. 5G Evolution: What's Next? *IEEE Wirel. Commun.* **2021**, *28*, 4–8. [CrossRef]
52. Ghosh, A.; Maeder, A.; Baker, M.; Chandramouli, D. 5G Evolution: A View on 5G Cellular Technology Beyond 3GPP Release 15. *IEEE Access* **2019**, *7*, 127639–127651. [CrossRef]
53. Romano, G. IMT-2020 Requirements and Realization. *Wiley 5G Ref.* **2019**, 1–28.

54. Series, M. Guidelines for Evaluation of Radio Interface Technologies for IMT-2020. *Report ITU* **2017**, 2410–2412.
55. 3GPP Study on New Services and Markets Technology Enablers. Available online: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2897 (accessed on 29 December 2022).
56. ITUR. *P.1814 Prediction Methods Required for the Design of Terrestrial Free-Space Optical Links*; International Telecommunication Union Radiocommunication Recommendations: Geneva, Switzerland, 2007.
57. Erunkulu, O.O.; Zungeru, A.M.; Lebekwe, C.K.; Mosalaosi, M.; Chuma, J.M. 5G Mobile Communication Applications: A Survey and Comparison of Use Cases. *IEEE Access* **2021**, *9*, 97251–97295. [CrossRef]
58. Li, C.-P.; Jiang, J.; Chen, W.; Ji, T.; Smee, J. 5G Ultra-Reliable and Low-Latency Systems Design. In Proceedings of the 2017 European Conference on Networks and Communications (EuCNC) 2017, Oulu, Finland, 12–15 June 2017.
59. Popovski, P.; Stefanovic, C.; Nielsen, J.J.; de Carvalho, E.; Angjelichinoski, M.; Trillingsgaard, K.F.; Bana, A.-S. Wireless Access in Ultra-Reliable Low-Latency Communication (URLLC). *IEEE Trans. Commun.* **2019**, *67*, 5783–5801. [CrossRef]
60. Siddiqi, M.A.; Yu, H.; Joung, J. 5G Ultra-Reliable Low-Latency Communication Implementation Challenges and Operational Issues with IoT Devices. *Electronics* **2019**, *8*, 981. [CrossRef]
61. Dutkiewicz, E.; Costa-Perez, X.; Kovacs, I.Z.; Mueck, M. Massive Machine-Type Communications. *IEEE Netw.* **2017**, *31*, 6–7. [CrossRef]
62. Massaro, M. Next Generation of Radio Spectrum Management: Licensed Shared Access for 5G. *Telecomm. Policy* **2017**, *41*, 422–433. [CrossRef]
63. Station, B. Radio Transmission and Reception (Release 15), 3GPP Technical Specification Group Radio Access Network; NR, TS 38.104, V15. 0.0. Dec. 2017. 2019. Available online: https://www.etsi.org/deliver/etsi_ts/138100_138199/138104/15.05.00_60/ts_138104v150500p.pdf (accessed on 29 December 2022).
64. Morgado, A.; Huq, K.M.S.; Mumtaz, S.; Rodriguez, J. A Survey of 5G Technologies: Regulatory, Standardization and Industrial Perspectives. *Digit. Commun. Netw.* **2018**, *4*, 87–97. [CrossRef]
65. Ancans, G.; Bobrovs, V.; Ancans, A.; Kalibatiene, D. Spectrum Considerations for 5G Mobile Communication Systems. *Procedia Comput. Sci.* **2017**, *104*, 509–516. [CrossRef]
66. Nasarre, I.P.; Levanen, T.; Pajukoski, K.; Lehti, A.; Tiirola, E.; Valkama, M. Enhanced Uplink Coverage for 5G NR: Frequency-Domain Spectral Shaping With Spectral Extension. *IEEE Open J. Commun. Soc.* **2021**, *2*, 1188–1204. [CrossRef]
67. Gohil, A.; Modi, H.; Patel, S.K. 5G Technology of Mobile Communication: A Survey. In Proceedings of the 2013 International Conference on Intelligent Systems and Signal Processing, ISSP 2013, Piscataway, NJ, USA, 1–2 March 2013; pp. 288–292.
68. Maddikunta, P.K.R.; Pham, Q.-V.; Prabadevi, B.; Deepa, N.; Dev, K.; Gadekallu, T.R.; Ruby, R.; Liyanage, M. Industry 5.0: A Survey on Enabling Technologies and Potential Applications. *J. Ind. Inf. Integr.* **2022**, *26*, 100257. [CrossRef]
69. Qiao, J.; Shen, X.; Mark, J.; Shen, Q.; He, Y.; Lei, L. Enabling Device-to-Device Communications in Millimeter-Wave 5G Cellular Networks. *IEEE Commun. Mag.* **2015**, *53*, 209–215. [CrossRef]
70. Wei, L.; Hu, R.; Qian, Y.; Wu, G. Key Elements to Enable Millimeter Wave Communications for 5G Wireless Systems. *IEEE Wirel. Commun.* **2014**, *21*, 136–143. [CrossRef]
71. Hong, W.; Baek, K.-H.; Ko, S. Millimeter-Wave 5G Antennas for Smartphones: Overview and Experimental Demonstration. *IEEE Trans. Antennas Propag.* **2017**, *65*, 6250–6261. [CrossRef]
72. Rappaport, T.S.; Xing, Y.; MacCartney, G.R.; Molisch, A.F.; Mellios, E.; Zhang, J. Overview of Millimeter Wave Communications for Fifth-Generation (5G) Wireless Networks-With a Focus on Propagation Models. *IEEE Trans. Antennas Propag.* **2017**, *65*, 6213–6230. [CrossRef]
73. Xiao, M.; Mumtaz, S.; Huang, Y.; Dai, L.; Li, Y.; Matthaiou, M.; Karagiannidis, G.K.; Bjornson, E.; Yang, K.; Chih-Lin, I.; et al. Millimeter Wave Communications for Future Mobile Networks. *IEEE J. Sel. Areas Commun.* **2017**, *35*, 1909–1935. [CrossRef]
74. Imoize, A.L.; Obakhena, H.I.; Anyasi, F.I.; Adelabu, M.A.; Kavitha, K.V.N.; Faruk, N. Spectral Efficiency Bounds of Cell-Free Massive MIMO Assisted UAV Cellular Communication. In Proceedings of the 2022 IEEE Nigeria 4th International Conference on Disruptive Technologies for Sustainable Development (NIGERCON) 2022, Abuja, Nigeria, 17–19 May 2022.
75. Brown, G. Exploring 5G New Radio: Use Cases, Capabilities and Timeline. *Heavy Read. Behalf Qualcomm* **2016**, 1–13.
76. Chen, S.Z.; Kang, S.L. A Tutorial on 5G and the Progress in China. *Front. Inf. Technol. Electron. Eng.* **2018**, *19*, 309–321. [CrossRef]
77. Obakhena, H.I.; Imoize, A.L.; Anyasi, F.I.; Kavitha, K.V.N. Application of Cell-Free Massive MIMO in 5G and beyond 5G Wireless Networks: A Survey. *J. Eng. Appl. Sci.* **2021**, *68*, 1–41. [CrossRef]
78. Prasad, K.N.R.S.V.; Hossain, E.; Bhargava, V.K. Energy Efficiency in Massive MIMO-Based 5G Networks: Opportunities and Challenges. *IEEE Wirel. Commun.* **2017**, *24*, 86–94. [CrossRef]
79. Lu, L.; Member, S.; Ye Li, G.; Lee Swindlehurst, A.; Ashikhmin, A.; Member, S.; Zhang, R. An Overview of Massive MIMO: Benefits and Challenges. *IEEE J. Sel. Top. Signal Process.* **2014**, *8*, 742–758. [CrossRef]
80. Hassan, N.; Fernando, X. Massive MIMO Wireless Networks: An Overview. *Electronics* **2017**, *6*, 63. [CrossRef]
81. Rosenberger, H.; Gäde, B.; Bereyhi, A.; Ahmed, D.; Jamali, V.; Müller, R.R.; Fischer, G.; He, G.; Debbah, M. A High-Level Comparison of Recent Technologies for Massive MIMO Architectures. *arXiv* **2022**, arXiv:2212.11842.
82. Ribeiro, F.C.; Dinis, R.; Cercas, F.; Silva, A. Receiver Design for the Uplink of Base Station Cooperation Systems Employing SC-FDE Modulations. *EURASIP J. Wirel. Commun. Netw.* **2015**, *2015*. [CrossRef]
83. Castanheira, D.; Silva, A.; Dinis, R.; Gameiro, A. Efficient Transmitter and Receiver Designs for SC-FDMA Based Heterogeneous Networks. *IEEE Trans. Commun.* **2015**, *63*, 2500–2510. [CrossRef]

84. Papadopoulos, H.; Wang, C.; Bursalioglu, O.; Hou, X.; Kishiyama, Y. Massive MIMO Technologies and Challenges towards 5G. *IEICE Trans. Commun.* **2016**, *E99.B*, 602–621. [CrossRef]
85. Imoize, A.L.; Obakhena, H.I.; Anyasi, F.I.; Sur, S.N. A Review of Energy Efficiency and Power Control Schemes in Ultra-Dense Cell-Free Massive MIMO Systems for Sustainable 6G Wireless Communication. *Sustainability* **2022**, *14*, 11100. [CrossRef]
86. Zhou, Y.; Li, D.; Wang, H.; Yang, A.; Guo, S. QoS-Aware Energy-Efficient Optimization for Massive MIMO Systems in 5G. In Proceedings of the 2014 Sixth International Conference on Wireless Communications and Signal Processing (WCSP) 2014, Hefei, China, 23–25 October 2014.
87. Chataut, R.; Akl, R. Massive MIMO Systems for 5G and Beyond Networks-Overview, Recent Trends, Challenges, and Future Research Direction. *Sensors* **2020**, *20*, 2753. [CrossRef]
88. Vaigandla, K.K.; Venu, N. Survey on Massive MIMO: Technology, Challenges, Opportunities and Benefits. *YMER Digit.* **2021**, *20*, 271–282. [CrossRef]
89. Tehrani, M.N.; Uysal, M.; Yanikomeroglu, H. Device-to-Device Communication in 5G Cellular Networks: Challenges, Solutions, and Future Directions. *IEEE Commun. Mag.* **2014**, *52*, 86–92. [CrossRef]
90. Li, Q.C.; Niu, H.; Papathanassiou, A.T.; Wu, G. 5G Network Capacity: Key Elements and Technologies. *IEEE Veh. Technol. Mag.* **2014**, *9*, 71–78. [CrossRef]
91. Fodor, G.; Dahlman, E.; Mildh, G.; Parkvall, S.; Reider, N.; Miklós, G.; Turányi, Z. Design Aspects of Network Assisted Device-to-Device Communications. *IEEE Commun. Mag.* **2012**, *50*, 170–177. [CrossRef]
92. Boban, M.; Kousaridas, A.; Manolakis, K.; Eichinger, J.; Xu, W. Use Cases, Requirements, and Design Considerations for 5G V2X. *arXiv* **2017**, arXiv:1712.01754.
93. Balasubramanian, V.; Aloqaily, M.; Reisslein, M. Mutes: Multi-Tenant Switching for 5G Network Slice Revenue Maximization. In Proceedings of the 2022 International Wireless Communications and Mobile Computing (IWCMC) 2022, Dubrovnik, Croatia, 30 May–3 June 2022.
94. Barakabitze, A.A.; Ahmad, A.; Mijumbi, R.; Hines, A. 5G Network Slicing Using SDN and NFV: A Survey of Taxonomy, Architectures and Future Challenges. *Comput. Netw.* **2020**, *167*, 106984. [CrossRef]
95. Madi, T.; Alameddine, H.A.; Pourzandi, M.; Boukhtouta, A. NFV Security Survey in 5G Networks: A Three-Dimensional Threat Taxonomy. *Comput. Netw.* **2021**, *197*, 108288. [CrossRef]
96. Park, J.H.; Rathore, S.; Singh, S.K.; Salim, M.M.; el Azzaoui, A.; Kim, T.W.; Pan, Y.; Park, J.H. A Comprehensive Survey on Core Technologies and Services for 5G Security: Taxonomies, Issues, and Solutions. *Hum. -Cent. Comput. Inf. Sci.* **2021**, *11*. [CrossRef]
97. Mandal, P. Comparison of Placement Variants of Virtual Network Functions From Availability and Reliability Perspective. *IEEE Trans. Netw. Serv. Manag.* **2022**, *19*, 860–874. [CrossRef]
98. Li, S.; Da Xu, L.; Zhao, S. 5G Internet of Things: A Survey. *J. Ind. Inf. Integr.* **2018**, *10*, 1–9. [CrossRef]
99. Mowla, M.M.; Ahmad, I.; Habibi, D.; Phung, Q.V. Energy Efficient Backhauling for 5G Small Cell Networks. *IEEE Trans. Sustain. Comput.* **2019**, *4*, 279–292. [CrossRef]
100. Sudarshan, P.; Mehta, N.; Molisch, A.; Zhang, J. Channel Statistics-Based RF Pre-Processing with Antenna Selection. *IEEE Trans. Wirel. Commun.* **2006**, *5*, 3501–3511. [CrossRef]
101. Faruk, N.; Abdulkarim, A.; Surajudeen-Bakinde, N.T.; Popoola, S.I. Energy Efficiency of Backhauling Options for Future Heterogeneous Networks. In *Green Energy and Technology*; Herawan, T., Chiroma, H., Abawajy, J.H., Eds.; Springer: Cham, Switzerland, 2019; pp. 169–194. ISBN 978-3-319-69889-2. [CrossRef]
102. Lee, J.; Friderikos, V. Robotic Aerial 6G Small Cells with Grasping End Effectors for MmWave Relay Backhauling. In Proceedings of the 2022 IEEE 33rd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC) 2022, Kyoto, Japan, 12–15 September 2022.
103. Islam, S.M.R.; Avazov, N.; Dobre, O.A.; Kwak, K.S. Power-Domain Non-Orthogonal Multiple Access (NOMA) in 5G Systems: Potentials and Challenges. *IEEE Commun. Surv. Tutor.* **2016**, *19*, 721–742. [CrossRef]
104. Marques da Silva, M.; Dinis, R. Power-Ordered NOMA with Massive MIMO for 5G Systems. *Appl. Sci.* **2021**, *11*, 3541. [CrossRef]
105. Wu, Q.; Li, G.Y.; Chen, W.; Ng, D.W.K.; Schober, R. An Overview of Sustainable Green 5G Networks. *IEEE Wirel. Commun.* **2017**, *24*, 72–80. [CrossRef]
106. Wei, Z.; Yuan, J.; Ng, D.W.K.; Elkashlan, M.; Ding, Z. A Survey of Downlink Non-Orthogonal Multiple Access for 5G Wireless Communication Networks. *arXiv* **2016**, arXiv:1609.01856.
107. Dai, L.; Wang, B.; Ding, Z.; Wang, Z.; Chen, S.; Hanzo, L. A Survey of Non-Orthogonal Multiple Access for 5G. *IEEE Commun. Surv. Tutor.* **2018**, *20*, 2294–2323. [CrossRef]
108. Lu, K.; Wu, Z.; Shao, X. A Survey of Non-Orthogonal Multiple Access for 5G. In Proceedings of the 2017 IEEE 86th Vehicular Technology Conference (VTC-Fall) 2017, Toronto, ON, Canada, 24–27 September 2017.
109. Popoola, S.I.; Faruk, N.; Atayero, A.A.; Oshin, M.A.; Bello, O.W.; Mutafungwa, E. Radio Access Technologies for Sustainable Deployment of 5G Networks in Emerging Markets. *Int. J. Appl. Eng. Res.* **2017**, *12*, 14154–14172.
110. Merin Joshiba, J.; Judson, D.; Albert Raj, A. 5G Modulation Techniques—A Systematic Literature Survey. *Futur. Commun. Netw. Technol.* **2021**, 351–372.
111. Khuntia, M.; Singh, D.; Sahoo, S. Impact of Internet of Things (IoT) on 5G. *Smart Innov. Syst. Technol.* **2020**, 125–136.
112. Goudos, S.K.; Dallas, P.I.; Chatziefthymiou, S.; Kyriazakos, S. A Survey of IoT Key Enabling and Future Technologies: 5G, Mobile IoT, Sematic Web and Applications. *Wirel. Pers. Commun.* **2017**, *97*, 1645–1675. [CrossRef]

113. Khurpade, J.M.; Rao, D.; Sanghavi, P.D. A Survey on IOT and 5G Network. In Proceedings of the 2018 International Conference on Smart City and Emerging Technology (ICSCET), Mumbai, India, 5 January 2018.
114. Marabissi, D.; Mucchi, L.; Fantacci, R.; Spada, M.; Massimiani, F.; Fratini, A.; Cau, G.; Yunpeng, J.; Fedele, L. A Real Case of Implementation of the Future 5G City. *Future Internet* **2018**, *11*, 4. [CrossRef]
115. Beck, M.T.; Werner, M.; Feld, S.; Schimper, T. Mobile Edge Computing: A Taxonomy. In Proceedings of the Sixth International Conference on Advances in Future Internet, Lisbon, Portugal, 16–20 November 2014; pp. 48–54.
116. Kim, G.H.; Pae, D.S.; Ahn, W.J.; Ko, K.S.; Lim, M.T.; Kang, T.K. Vehicle Positioning System Using V2X That Combines V2V and V2I Communications. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *922*, 12009. [CrossRef]
117. Zhang, N.; Cheng, N.; Gamage, A.T.; Zhang, K.; Mark, J.W.; Shen, X. Cloud Assisted HetNets toward 5G Wireless Networks. *IEEE Commun. Mag.* **2015**, *53*, 59–65. [CrossRef]
118. Andrews, J.G.; Zhang, X.; Durgin, G.D.; Gupta, A.K. Are We Approaching the Fundamental Limits of Wireless Network Densification? *IEEE Commun. Mag.* **2016**, *54*, 184–190. [CrossRef]
119. Liu, J.; Sheng, M.; Liu, L.; Li, J. Network Densification in 5G: From the Short-Range Communications Perspective. *IEEE Commun. Mag.* **2017**, *55*, 96–102. [CrossRef]
120. Thurfjell, M.; Ericsson, M.; de Bruin, P. Network Densification Impact on System Capacity. In Proceedings of the 2015 IEEE 81st Vehicular Technology Conference (VTC Spring) 2015, Glasgow, UK, 11–14 May 2015.
121. Nidhi; Mihovska, A.; Prasad, R. Overview of 5G New Radio and Carrier Aggregation: 5G and Beyond Networks. In Proceedings of the 2020 23rd International Symposium on Wireless Personal Multimedia Communications (WPMC) 2020, Okayama, Japan, 19–26 October 2020.
122. Alkhansa, R.; Artail, H.; Gutierrez-Estevez, D.M. LTE-WiFi Carrier Aggregation for Future 5G Systems: A Feasibility Study and Research Challenges. *Procedia Comput. Sci.* **2014**, *34*, 133–140. [CrossRef]
123. Shafi, M.; Molisch, A.F.; Smith, P.J.; Haustein, T.; Zhu, P.; De Silva, P.; Tufvesson, F.; Benjebbour, A.; Wunder, G. 5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice. *IEEE J. Sel. Areas Commun.* **2017**, *35*, 1201–1221. [CrossRef]
124. Parikh, J.; Basu, A. Scheduling schemes for carrier aggregation in lte-advanced systems. *Int. J. Res. Eng. Technol.* **2014**, *3*, 219–223. [CrossRef]
125. Joda, R.; Elsayed, M.; Abou-Zeid, H.; Atawia, R.; Sediq, A.B.; Boudreau, G.; Erol-Kantarci, M. QoS-Aware Joint Component Carrier Selection and Resource Allocation for Carrier Aggregation in 5G. In Proceedings of the ICC 2021—IEEE International Conference on Communications 2021, Montreal, QC, Canada, 14–23 June 2021.
126. Joda, R.; Elsayed, M.; Abou-Zeid, H.; Atawia, R.; Sediq, A.B.; Boudreau, G.; Erol-Kantarci, M. Carrier Aggregation With Optimized UE Power Consumption in 5G. *IEEE Netw. Lett.* **2021**, *3*, 61–65. [CrossRef]
127. Afolalu, O.; Ventura, N. Carrier Aggregation-Enabled Non-Orthogonal Multiple Access Approach towards Enhanced Network Performance in 5G Ultra-Dense Networks. *Int. J. Commun. Syst.* **2020**, *34*. [CrossRef]
128. Konstantinou, D.; Morales, A.; Rommel, S.; Raddo, T.R.; Johannsen, U.; Monroy, I.T. Analog Radio Over Fiber Fronthaul for High Bandwidth 5G Millimeter-Wave Carrier Aggregated OFDM. In Proceedings of the 2019 21st International Conference on Transparent Optical Networks (ICTON) 2019, Angers, France, 9–13 July 2019.
129. Ahmad, W.S.H.M.W.; Radzi, N.A.M.; Samidi, F.S.; Ismail, A.; Abdullah, F.; Jamaludin, M.Z.; Zakaria, M.N. 5G Technology: Towards Dynamic Spectrum Sharing Using Cognitive Radio Networks. *IEEE Access* **2020**, *8*, 14460–14488. [CrossRef]
130. Mueck, M.D.; Srikanteswara, S.; Badic, B. Spectrum Sharing: Licensed Shared Access (LSA) and Spectrum Access System (SAS). *Intel White Pap.* **2015**, 1–26.
131. Mitra, R.N.; Agrawal, D.P. 5G Mobile Technology: A Survey. *ICT Express* **2015**, *1*, 132–137. [CrossRef]
132. Pirinen, P. A Brief Overview of 5G Research Activities. In Proceedings of the 1st International Conference on 5G for Ubiquitous Connectivity 2014, Levi, Finland, 26–27 November 2014.
133. Fonyi, S. Overview of 5G Security and Vulnerabilities. *Cyber Def. Rev.* **2020**, *5*, 117–134.
134. Sullivan, S.; Brighente, A.; Kumar, S.A.P.; Conti, M. 5G Security Challenges and Solutions: A Review by OSI Layers. *IEEE Access* **2021**, *9*, 116294–116314. [CrossRef]
135. Moudoud, H.; Cherkaoui, S.; Khoukhi, L. An Overview of Blockchain and 5G Networks. *EAI/Springer Innov. Commun. Comput.* **2021**, 1–20.
136. Nguyen, D.C.; Pathirana, P.N.; Ding, M.; Seneviratne, A. Blockchain for 5G and beyond Networks: A State of the Art Survey. *J. Netw. Comput. Appl.* **2020**, *166*, 102693. [CrossRef]
137. Vanelli-Coralli, A.; Guidotti, A.; Foggi, T.; Colavolpe, G.; Montorsi, G. 5G and beyond 5G Non-Terrestrial Networks: Trends and Research Challenges. In Proceedings of the 2020 IEEE 3rd 5G World Forum, 5GWF 2020—Conference Proceedings, Bangalore, India, 10–12 September 2020.
138. Hokazono, Y.; Kishiyama, Y.; Asai, T. Research on NTN Technology for 5G Evolution & 6G. *NTT Tech. Rev.* **2021**, *19*. [CrossRef]
139. Hosseinian, M.; Choi, J.P.; Chang, S.H.; Lee, J. Review of 5G NTN Standards Development and Technical Challenges for Satellite Integration with the 5G Network. *IEEE Aerosp. Electron. Syst. Mag.* **2021**, *36*. [CrossRef]
140. Sedin, J.; Gopinath, S.; Lin, X.; Liberg, O.; Khan, T.; Yavuz, E.; Euler, S. 5G Massive Machine Type Communication Performance in Non-Terrestrial Networks with LEO Satellites. In Proceedings of the 2021 IEEE Global Communications Conference, GLOBECOM 2021—Proceedings, Madrid, Spain, 7–11 December 2021.

141. Vaezi, M.; Azari, A.; Khosravirad, S.R.; Shirvanimoghaddam, M.; Azari, M.M.; Chasaki, D.; Popovski, P. Cellular, Wide-Area, and Non-Terrestrial IoT: A Survey on 5G Advances and the Road toward 6G. *IEEE Commun. Surv. Tutor.* **2022**, *24*, 1117–1174. [CrossRef]
142. Qiao, L.; Yan, H.; Zhou, X.; Xu, Y.; Wang, L.; Wen, X. Onboard Centralized ISL-Building Planning for LEO Satellite Constellation Networks. *Electronics* **2023**, *12*, 635. [CrossRef]
143. Ye, J.; Qiao, J.; Kammoun, A.; Alouini, M.S. Non-Terrestrial Communications Assisted by Reconfigurable Intelligent Surfaces. *Proc. IEEE* **2022**. [CrossRef]
144. Jiang, Y.; Wu, S.; Mo, Q.; Liu, W.; Wei, X. An Energy Sensitive and Congestion Balance Routing Scheme for Non-Terrestrial-Satellite-Network (NTSN). *Remote Sens.* **2023**, *15*, 585. [CrossRef]
145. Study on New Radio (NR) to Support Non-Terrestrial Networks (NTN). Document TR 38.811, Release 15,3GPP 2019. Available online: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3234 (accessed on 19 November 2022).
146. Study on Using Satellite Access in 5G. Document TR 22.822, Release 16, 3GPP. June 2018. Available online: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3372 (accessed on 19 November 2022).
147. Lin, X. An Overview of 5G Advanced Evolution in 3GPP Release 18. *IEEE Commun. Stand. Mag.* **2022**, *6*, 77–83. [CrossRef]
148. Lin, X.; Rommer, S.; Euler, S.; Yavuz, E.A.; Karlsson, R.S. 5G from Space: An Overview of 3GPP Non-Terrestrial Networks. *IEEE Commun. Stand. Mag.* **2021**, *5*. [CrossRef]
149. Azari, M.M.; Solanki, S.; Chatzinotas, S.; Kodheli, O.; Sallouha, H.; Colpaert, A.; Mendoza Montoya, J.F.; Pollin, S.; Haqiqatnejad, A.; Mostaani, A.; et al. Evolution of Non-Terrestrial Networks from 5G to 6G: A Survey. *IEEE Commun. Surv. Tutor.* **2022**, *24*, 2633–2672. [CrossRef]
150. Rinaldi, F.; Määttänen, H.L.; Torsner, J.; Pizzi, S.; Andreev, S.; Iera, A.; Koucheryavy, Y.; Araniti, G. Non-Terrestrial Networks in 5G & beyond: A Survey. *IEEE Access* **2020**, *8*, 165178–165200. [CrossRef]
151. 3GPP Solutions for NR to Support Non-Terrestrial Networks (NTN) (Release 16). TR 38.821 V16.1.0 Release 16 May 2021. Available online: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3525 (accessed on 29 December 2022).
152. 5G Americas. 5G & Non-Terrestrial Networks. February 2022. Available online: https://www.5gamericas.org/5g-and-non-terrestrial-networks/ (accessed on 29 December 2022).
153. ITU. Provisional Final Acts. In Proceedings of the World Radiocommunication Conference 2019, Sharm El-Sheikh, Egypt, 28 October–22 November 2019; 2019.
154. Union, A. Report of the 3rd Ordinary Session of the Specialized Technical Committee on Communication and ICT, Sharm El Sheikh, Egypt, 25–26 October 2019. 2020. Available online: https://au.int/en/documents/20191025/ministerial-report-3rd-ordinary-session-african-union-specialized-technical (accessed on 5 December 2022).
155. Sowande, O.A.; Idachaba, F.E.; Ekpo, S.; Faruk, N.; Uko, M.; Ogunmodimu, O. Sub- 6 GHz 5G Spectrum for Satellite-Cellular Convergence Broadband Internet Access in Nigeria. *Int. Rev. Aerosp. Eng. (IREASE)* **2022**, *15*, 85. [CrossRef]
156. Dilli, R. Analysis of 5G Wireless Systems in FR1 and FR2 Frequency Bands. In Proceedings of the 2020 2nd International Conference on Innovative Mechanisms for Industry Applications (ICIMIA) 2020, Bangalore, India, 5–7 March 2020.
157. Faruk, N.; Bello, O.W.; Sowande, O.A.; Onidare, S.O.; Muhammad, M.Y.; Ayeni, A.A. Large Scale Spectrum Survey in Rural and Urban Environments within the 50 MHz–6 GHz Bands. *Measurement* **2016**, *91*, 228–238. [CrossRef]
158. Salami, G.; Faruk, N.; Surajudeen-Bakinde, N.; Ngobigha, F. Challenges and Trends in 5G Deployment: A Nigerian Case Study. In Proceedings of the 2019 2nd International Conference of the IEEE Nigeria Computer Chapter (NigeriaComputConf) 2019, Zaria, Nigeria, 14–17 October 2019.
159. Kumar, S.; Kumar, A. 5G New Radio Deployment Modes. *Int. Res. J. Eng. Technol. (IRJET)* **2020**, 3419–3422.
160. Marcus, M.; Pattan, B. Millimeter Wave Propagation: Spectrum Management Implications. *IEEE Microw. Mag.* **2005**, *6*, 54–62. [CrossRef]
161. Adebowale, Q.R.; Faruk, N.; Adewole, K.S.; Abdulkarim, A.; Olawoyin, L.A.; Oloyede, A.A.; Chiroma, H.; Usman, A.D.; Calafate, C.T. Application of Computational Intelligence Algorithms in Radio Propagation: A Systematic Review and Metadata Analysis. *Mob. Inf. Syst.* **2021**, *2021*, 1–20. [CrossRef]
162. Imoize, A.L.; Ibhaze, A.E.; Atayero, A.A.; Kavitha, K.V.N. Standard Propagation Channel Models for MIMO Communication Systems. *Wirel. Commun. Mob. Comput.* **2021**, *2021*, 1–36. [CrossRef]
163. Shafi, M.; Zhang, J.; Tataria, H.; Molisch, A.F.; Sun, S.; Rappaport, T.S.; Tufvesson, F.; Wu, S.; Kitao, K. Microwave vs. Millimeter-Wave Propagation Channels: Key Differences and Impact on 5G Cellular Systems. *IEEE Commun. Mag.* **2018**, *56*, 14–20. [CrossRef]
164. Andersen, J.B.; Rappaport, T.S.; Yoshida, S. Propagation Measurements and Models for Wireless Communications Channels. *IEEE Commun. Mag.* **1995**, *33*, 42–49. [CrossRef]
165. Faruk, N.; Adebowale, Q.R.; Olayinka, I.-F.Y.; Adewole, K.S.; Abdulkarim, A.; Oloyede, A.A.; Chiroma, H.; Sowande, O.A.; Olawoyin, L.A.; Garba, S.; et al. ANN-Based Model for Multiband Path Loss Prediction in Built-up Environments. *Sci. Afr.* **2022**, *17*, e01350. [CrossRef]
166. Smith, E.K. Centimeter and Millimeter Wave Attenuation and Brightness Temperature Due to Atmospheric Oxygen and Water Vapor. *Radio Sci.* **1982**, *17*, 1455–1464. [CrossRef]

167. Alozie, E.; Abdulkarim, A.; Abdullahi, I.; Usman, A.D.; Faruk, N.; Olayinka, I.-F.Y.; Adewole, K.S.; Oloyede, A.A.; Chiroma, H.; Sowande, O.A.; et al. A Review on Rain Signal Attenuation Modeling, Analysis and Validation Techniques: Advances, Challenges and Future Direction. *Sustainability* **2022**, *14*, 11744. [CrossRef]
168. Faruk, N.; Abdulrasheed, I.Y.; Surajudeen-Bakinde, N.T.; Adetiba, E.; Oloyede, A.A.; Abdulkarim, A.; Sowande, O.; Ifijeh, A.H.; Atayero, A.A. Large-Scale Radio Propagation Path Loss Measurements and Predictions in the VHF and UHF Bands. *Heliyon* **2021**, *7*, e07298. [CrossRef]
169. Docomo, N. White Paper on 5G Channel Model for Bands up to 100 GHz; Tech. Rep. 2016. Available online: http://www.5gworkshops.com/5GCM.html (accessed on 5 December 2022).
170. Du, K.; Ozdemir, O.; Erden, F.; Guvenc, I. Sub-Terahertz and MmWave Penetration Loss Measurements for Indoor Environments. In Proceedings of the 2021 IEEE International Conference on Communications Workshops (ICC Workshops), Montreal, QC, Canada, 14–23 June 2021.
171. Samad, M.A.; Diba, F.D.; Kim, Y.J.; Choi, D.Y. Results of Large-Scale Propagation Models in Campus Corridor at 3.7 and 28 Ghz. *Sensors* **2021**, *21*, 7747. [CrossRef] [PubMed]
172. Adegoke, E.I.; Kampert, E.; Higgins, M.D. Empirical Indoor Path Loss Models at 3. In 5GHz for 5G Communications Network Planning. In Proceedings of the 2020 International Conference on UK-China Emerging Technologies (UCET) 2020, Glasgow, UK, 20–21 August 2020.
173. Medbo, J.; Kyösti, P.; Kusume, K.; Raschkowski, L.; Haneda, K.; Jamsa, T.; Nurmela, V.; Roivainen, A.; Meinilä, J. Radio Propagation Modeling for 5G Mobile and Wireless Communications. *IEEE Commun. Mag.* **2016**, *54*, 144–151. [CrossRef]
174. Huang, J.; Liu, Y.; Wang, C.X.; Sun, J.; Xiao, H. 5G Millimeter Wave Channel Sounders, Measurements, and Models: Recent Developments and Future Challenges. *IEEE Commun. Mag.* **2019**, *57*, 138–145. [CrossRef]
175. Singh, D.; Ouamri, M.A.; Muthanna, M.S.A.; Adam, A.B.M.; Muthanna, A.; Koucheryavy, A.; El-Latif, A.A.A. A Generalized Approach on Outage Performance Analysis of Dual-Hop Decode and Forward Relaying for 5G and beyond Scenarios. *Sustainability* **2022**, *14*, 12870. [CrossRef]
176. Ouamri, M.A.; Azni, M.; Oteşteanu, M.E. Coverage Analysis in Two-Tier 5G Hetnet Based on Stochastic Geometry with Interference Coordination Strategy. *Wirel. Pers. Commun.* **2021**, *121*, 3213–3222. [CrossRef]
177. Ouamri, M.A. Stochastic Geometry Modeling and Analysis of Downlink Coverage and Rate in Small Cell Network. *Telecommun. Syst.* **2021**, *77*, 767–779. [CrossRef]
178. Riviello, D.G.; Tuninato, R.; Zimaglia, E.; Fantini, R.; Garello, R. Implementation of Deep-Learning-Based CSI Feedback Reporting on 5G NR-Compliant Link-Level Simulator. *Sensors* **2023**, *23*, 910. [CrossRef] [PubMed]
179. "Study on Channel Model for Frequencies from 0.5 to 100 GHz." 3rd Generation Partnership Project;Technical Specification Group Radio Access Network. Available online: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3173 (accessed on 29 December 2022).
180. Hossain, E.; Rasti, M.; Tabassum, H.; Abdelnasser, A. Evolution toward 5G Multi-Tier Cellular Wireless Networks: An Interference Management Perspective. *IEEE Wirel. Commun.* **2014**, *21*, 118–127. [CrossRef]
181. Siddiqui, M.U.A.; Qamar, F.; Ahmed, F.; Nguyen, Q.N.; Hassan, R. Interference Management in 5G and Beyond Network: Requirements, Challenges and Future Directions. *IEEE Access* **2021**, *9*, 68932–68965. [CrossRef]
182. Panwar, N.; Sharma, S.; Singh, A.K. A Survey on 5G: The next Generation of Mobile Communication. *Phys. Commun.* **2016**, *18*, 64–84. [CrossRef]
183. Chih-Lin, I.; Rowell, C.; Han, S.; Xu, Z.; Li, G.; Pan, Z. Toward Green and Soft: A 5G Perspective. *IEEE Commun. Mag.* **2014**, *52*, 66–73. [CrossRef]
184. Karaboytcheva, M. Effects of 5G Wireless Communication on Human Health. *Brief. Eur. Parliam.* **2020**.
185. Chiaraviglio, L.; Elzanaty, A.; Alouini, M.-S. Health Risks Associated With 5G Exposure: A View From the Communications Engineering Perspective. *IEEE Open J. Commun. Soc.* **2021**, *2*, 2131–2179. [CrossRef]
186. Agubor, C.K.; Chukwuchekwa, N.; Ezema, L.S. 5G Network Deployment in Nigeria: Key Challenges and The Way Forward. *Eur. J. Eng. Technol. Res.* **2021**, *6*, 16–19. [CrossRef]
187. Mor, P.; Bajaj, S.B. Enabling Technologies and Architecture for 5G-Enabled IoT. *Blockchain 5G-Enabled IoT* **2021**, 223–259.
188. Sun, S.; Rappaport, T.S.; Shafi, M.; Tang, P.; Zhang, J.; Smith, P.J. Propagation Models and Performance Evaluation for 5G Millimeter-Wave Bands. *IEEE Trans. Veh. Technol.* **2018**, *67*, 8422–8439. [CrossRef]
189. Wang, C.X.; Bian, J.; Sun, J.; Zhang, W.; Zhang, M. A Survey of 5g Channel Measurements and Models. *IEEE Commun. Surv. Tutor.* **2018**, *20*, 3142–3168. [CrossRef]
190. Chow, M.C.; Ma, M. A Secure Blockchain-Based Authentication and Key Agreement Scheme for 3GPP 5G Networks. *Sensors* **2022**, *22*, 4525. [CrossRef]
191. William, P.; Yogeesh, N.; Vimala, S.; Gite, P.; Selva Kumar, S. Blockchain Technology for Data Privacy Using Contract Mechanism for 5G Networks. In Proceedings of the 3rd International Conference on Intelligent Engineering and Management, ICIEM 2022 2022, London, UK, 27–29 April 2022; pp. 461–465.
192. Han, S.; Bian, S. Energy-Efficient 5G for a Greener Future. *Nat. Electron.* **2020**, *3*, 182–184. [CrossRef]
193. Mohamed, K.S.; Alias, M.Y.; Roslee, M.; Raji, Y.M. Towards Green Communication in 5G Systems: Survey on Beamforming Concept. *IET Commun.* **2020**, *15*, 142–154. [CrossRef]
194. Zhang, S.; Cai, X.; Zhou, W.; Wang, Y. Green 5G Enabling Technologies: An Overview. *IET Commun.* **2019**, *13*, 135–143. [CrossRef]

195. Zhang, X.; Manogaran, G.; Muthu, B. IoT Enabled Integrated System for Green Energy into Smart Cities. *Sustain. Energy Technol. Assess.* **2021**, *46*, 101208. [CrossRef]
196. Gapeyenko, M.; Petrov, V.; Moltchanov, D.; Akdeniz, M.R.; Andreev, S.; Himayat, N.; Koucheryavy, Y. On the Degree of Multi-Connectivity in 5G Millimeter-Wave Cellular Urban Deployments. *IEEE Trans. Veh. Technol.* **2019**, *68*, 1973–1978. [CrossRef]
197. Sylla, T.; Mendiboure, L.; Maaloul, S.; Aniss, H.; Chalouf, M.A.; Delbruel, S. Multi-Connectivity for 5G Networks and Beyond: A Survey. *Sensors* **2022**, *22*, 7591. [CrossRef]
198. Ansari, R.I.; Pervaiz, H.; Hassan, S.A.; Chrysostomou, C.; Imran, M.A.; Mumtaz, S.; Tafazolli, R. A New Dimension to Spectrum Management in IoT Empowered 5G Networks. *IEEE Netw.* **2019**, *33*, 186–193. [CrossRef]
199. Harjula, I.; Panizo, L.; Valera-Muros, B.; Pinola, J.; Hoppari, M.; Flizikowski, A.; Safianowska, M. Dynamic Spectrum Management for European-Wide Research Network. In Proceedings of the 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring) 2020, Antwerp, Belgium, 25–28 May 2020.
200. Jian, M.; Alexandropoulos, G.C.; Basar, E.; Huang, C.; Liu, R.; Liu, Y.; Yuen, C. Reconfigurable Intelligent Surfaces for Wireless Communications: Overview of Hardware Designs, Channel Models, and Estimation Techniques. *Intell. Converg. Netw.* **2022**, *3*, 1–32. [CrossRef]
201. Christos Liaskos, B.; Schmid, S.; Akyildiz, I.F.; Mamatas, L.; Pitsillides, A. Software-Defined Reconfigurable Intelligent Surfaces: From Theory to End-to-End Implementation. *Proc. IEEE* **2022**, *110*, 1466–1493. [CrossRef]
202. Dajer, M.; Ma, Z.; Piazzi, L.; Prasad, N.; Qi, X.F.; Sheen, B.; Yang, J.; Yue, G. Reconfigurable Intelligent Surface: Design the Channel—a New Opportunity for Future Wireless Networks. *Digit. Commun. Netw.* **2022**, *8*, 87–104. [CrossRef]
203. Jiang, W. Graph-Based Deep Learning for Communication Networks: A Survey. *Comput. Commun.* **2022**, *185*, 40–54. [CrossRef]
204. He, S.; Xiong, S.; Ou, Y.; Zhang, J.; Wang, J.; Huang, Y.; Zhang, Y. An Overview on the Application of Graph Neural Networks in Wireless Networks. *IEEE Open J. Commun. Soc.* **2021**, *2*, 2547–2565. [CrossRef]
205. Lee, M.; Student Member, G.; Yu, G.; Member, S.; Dai, H.; Ye Li, G. Graph Neural Networks Meet Wireless Communications: Motivation, Applications, and Future Directions. *IEEE Wirel. Commun.* **2022**, *29*, 12–19. [CrossRef]
206. Yang, W.; Du, H.; Qin Liew, Z.; Yang Bryan Lim, W.; Xiong, Z.; Niyato, D.; Chi, X.; Sherman Shen, X.; Miao, C.; Yang, W.; et al. Semantic Communications for Future Internet: Fundamentals, Applications, and Challenges. *IEEE Commun. Surv. Tutor.* **2022**. [CrossRef]
207. Zhang, P.; Xu, W.; Gao, H.; Niu, K.; Xu, X.; Qin, X.; Yuan, C.; Qin, Z.; Zhao, H.; Wei, J.; et al. Toward Wisdom-Evolutionary and Primitive-Concise 6G: A New Paradigm of Semantic Communication Networks. *Engineering* **2022**, *8*, 60–73. [CrossRef]
208. Iyer, S.; Khanai, R.; Torse, D.; Pandya, R.J.; Rabie, K.M.; Pai, K.; Khan, W.U.; Fadlullah, Z. A Survey on Semantic Communications for Intelligent Wireless Networks. *Wirel. Pers. Commun.* **2023**, *129*, 569–611. [CrossRef]
209. Luo, X.; Chen, H.; Guo, Q. Semantic Communications: Overview, Open Issues, and Future Research Directions. *IEEE Wirel. Commun.* **2022**, *29*, 210–219. [CrossRef]
210. Zayas, A.D.; Salmerón, A.; Merino, P.; Cattoni, A.F.; Madueno, G.C.; Diedonne, M.; Carlier, F.; Saint Germain, B.; Morris, D.; Figueiredo, R. Triangle: 5G Applications and Devices Benchmarking. In *Building the Future Internet through FIRE*; River Publishers: New York, NY, USA, 2022; pp. 561–572.